New Probes of the Neutron Star Crust

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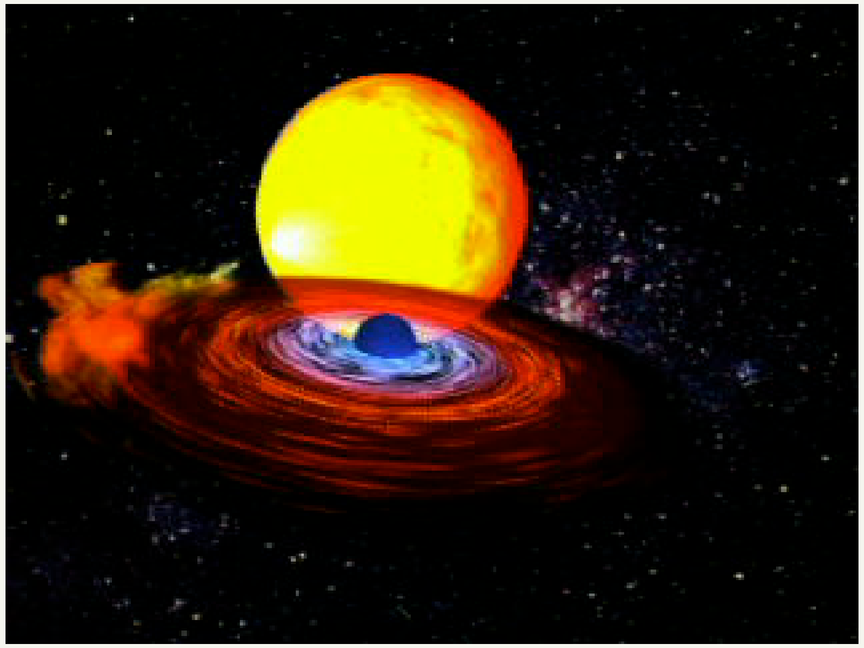
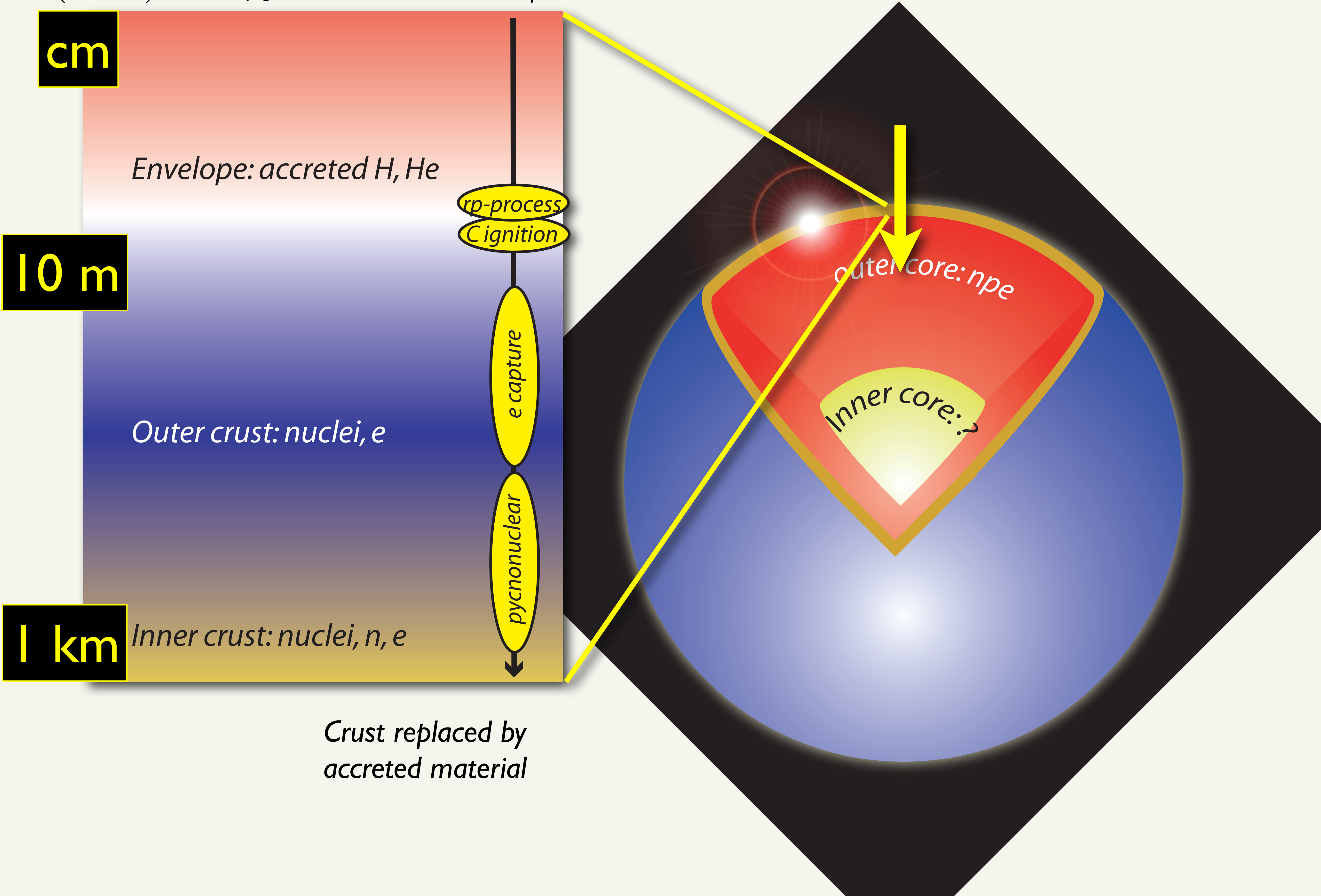


In this talk

- X-ray bursts, superbursts
  - Dependence on deep crustal heating
- Quasi-persistent transients
  - Crust cooling detected
  - Implications for crust structure
- Confrontation between these two methods

$$-\left(\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}r}\right)^{-1} = \frac{P}{\rho g}$$

$$v = \frac{\dot{m}}{\rho}$$



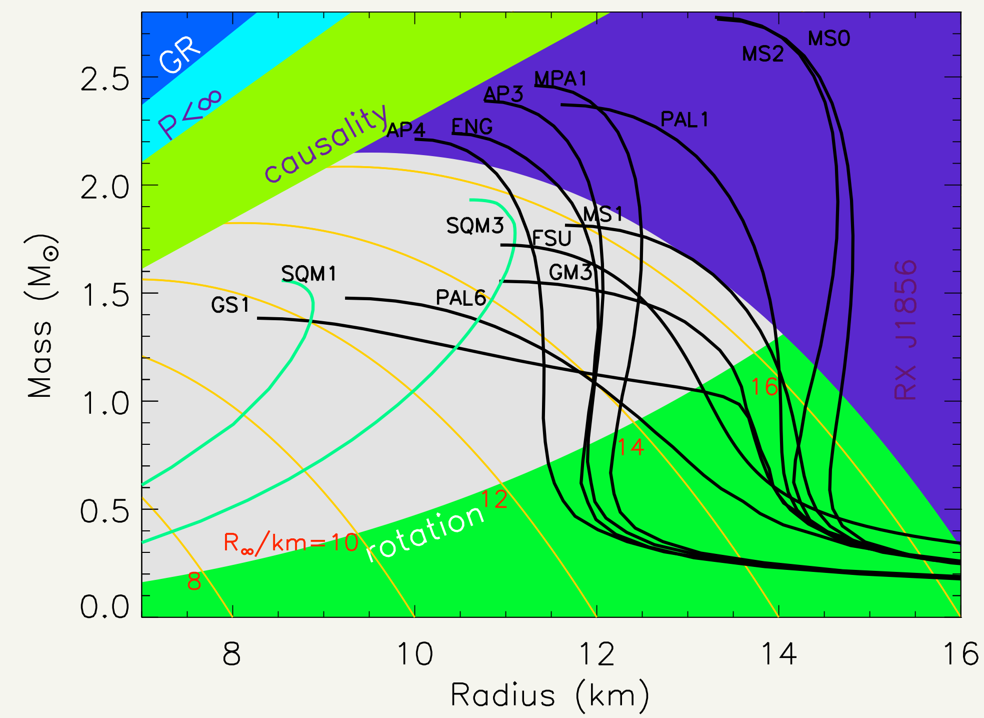
Crust replaced by accreted material

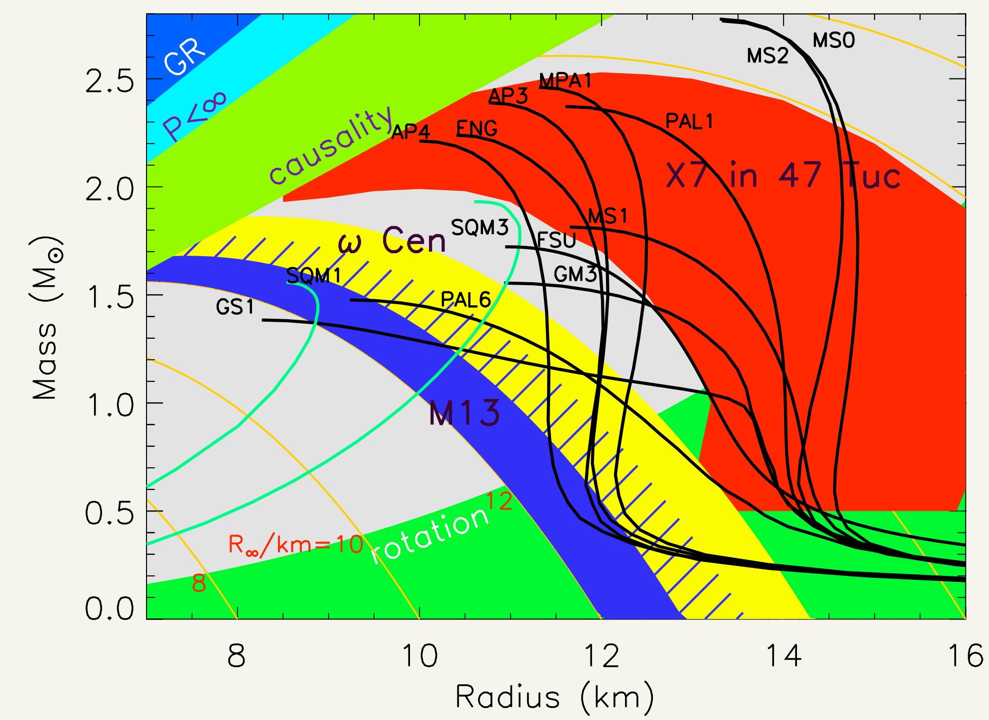
what can we learn?

- Strength and distribution of crust heat sources
- Thermal properties of crust
  - composition
  - conductivity
- Bulk properties of neutron star (M, R)

crust reactions

- explains quiescent luminosity of transients
  - constrain neutrino emissivity of core (Yakovlev et al. 05)
  - radius measurements (Rutledge et al 99; many more—see talk by Prakash)
- sets ignition mass for long X-ray bursts (this talk)

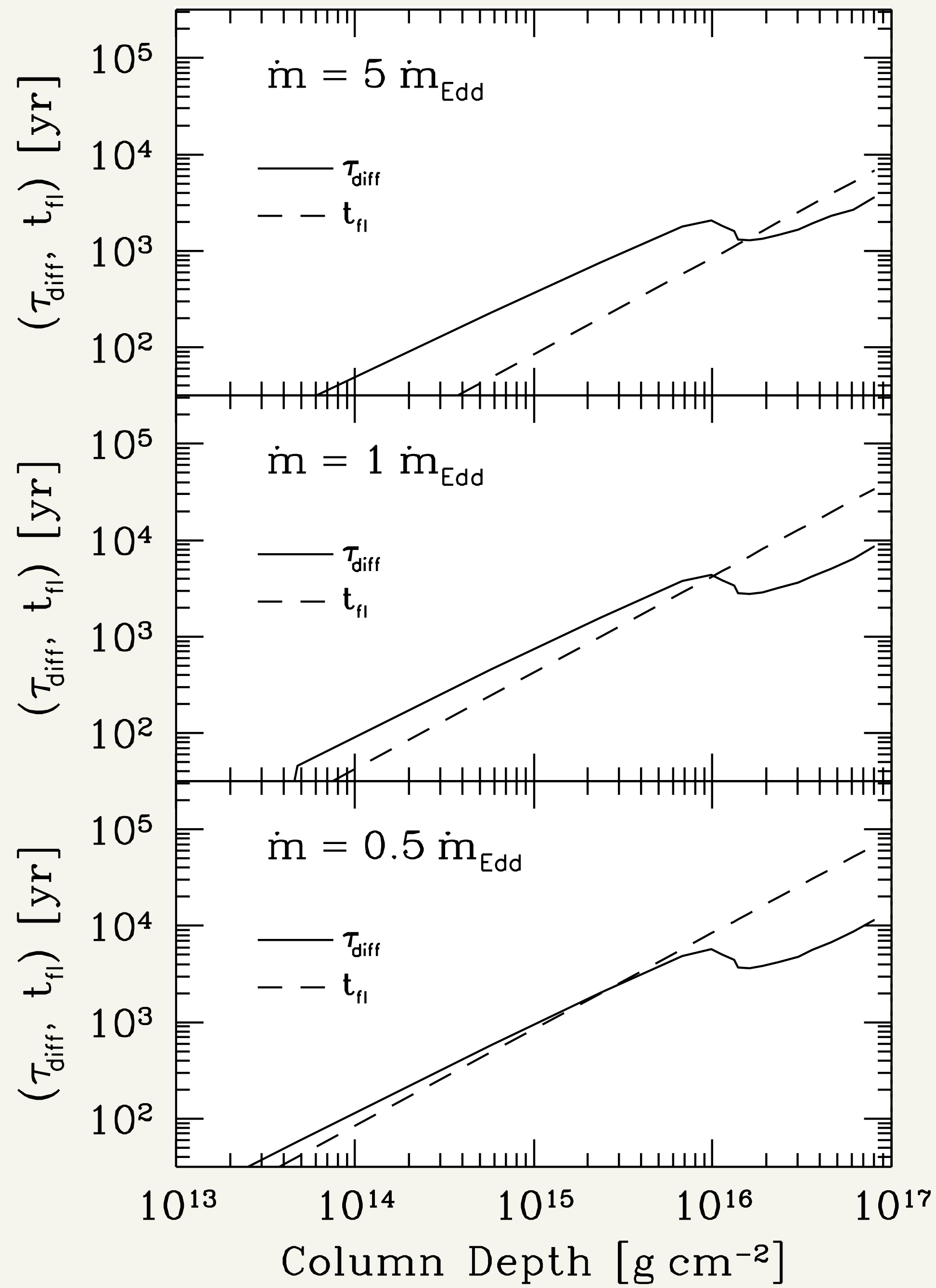




Lattimer & Prakash 07

crust reactions

- set electrical conductivity (controls ohmic decay)

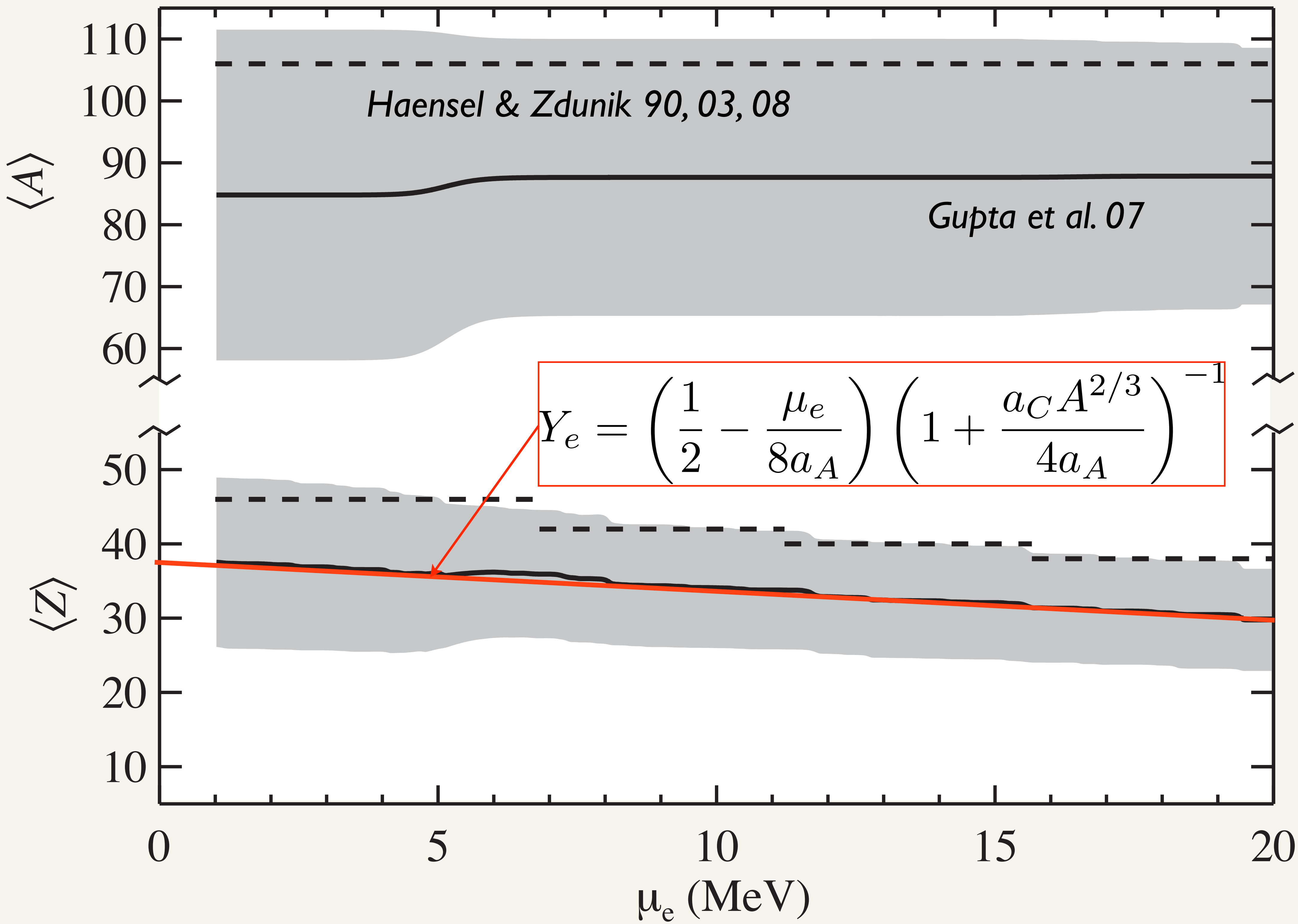


Konar & Bhattacharya 97,
Brown & Bildsten 98,
Cumming et al. 01

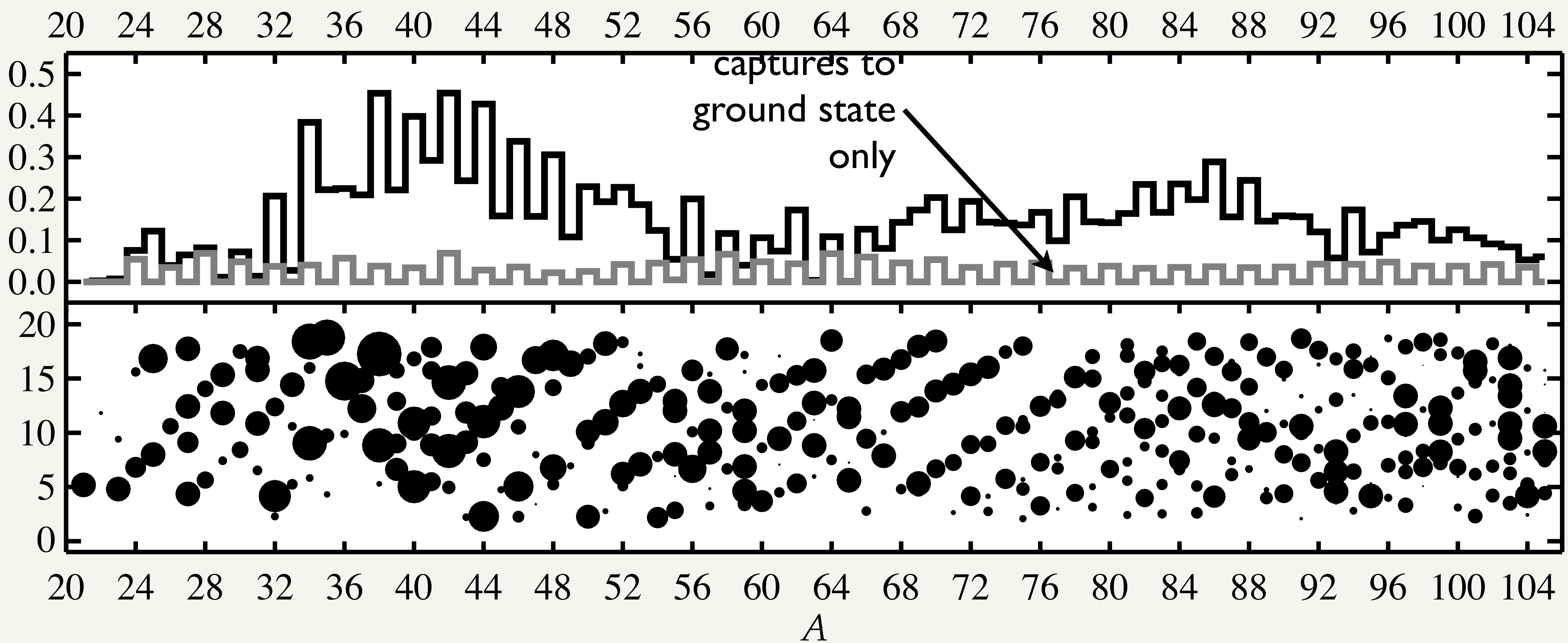
crust reactions

- Mass quadrupole—”mountain”—from composition inhomogeneities (Bildsten 98, Ushomirsky 00)
- r-mode damping (constrain existence of steady-state, Brown & Ushomirsky 00)

$$\frac{E}{A} = -a_V + a_S A^{-1/3} + a_A \left(\frac{N-Z}{N+Z}\right)^2 + a_C \frac{Z^2}{A^{4/3}}.$$



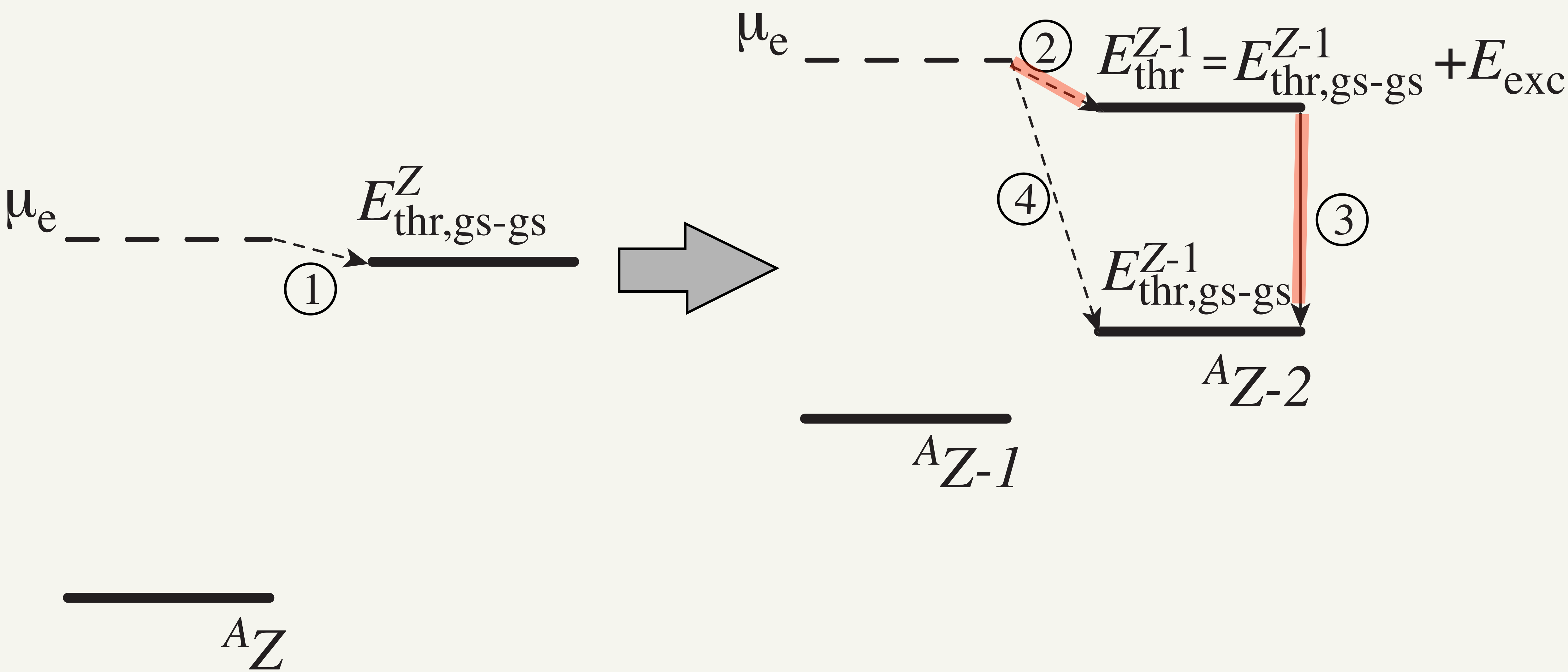
electron capture reactions, outer crust



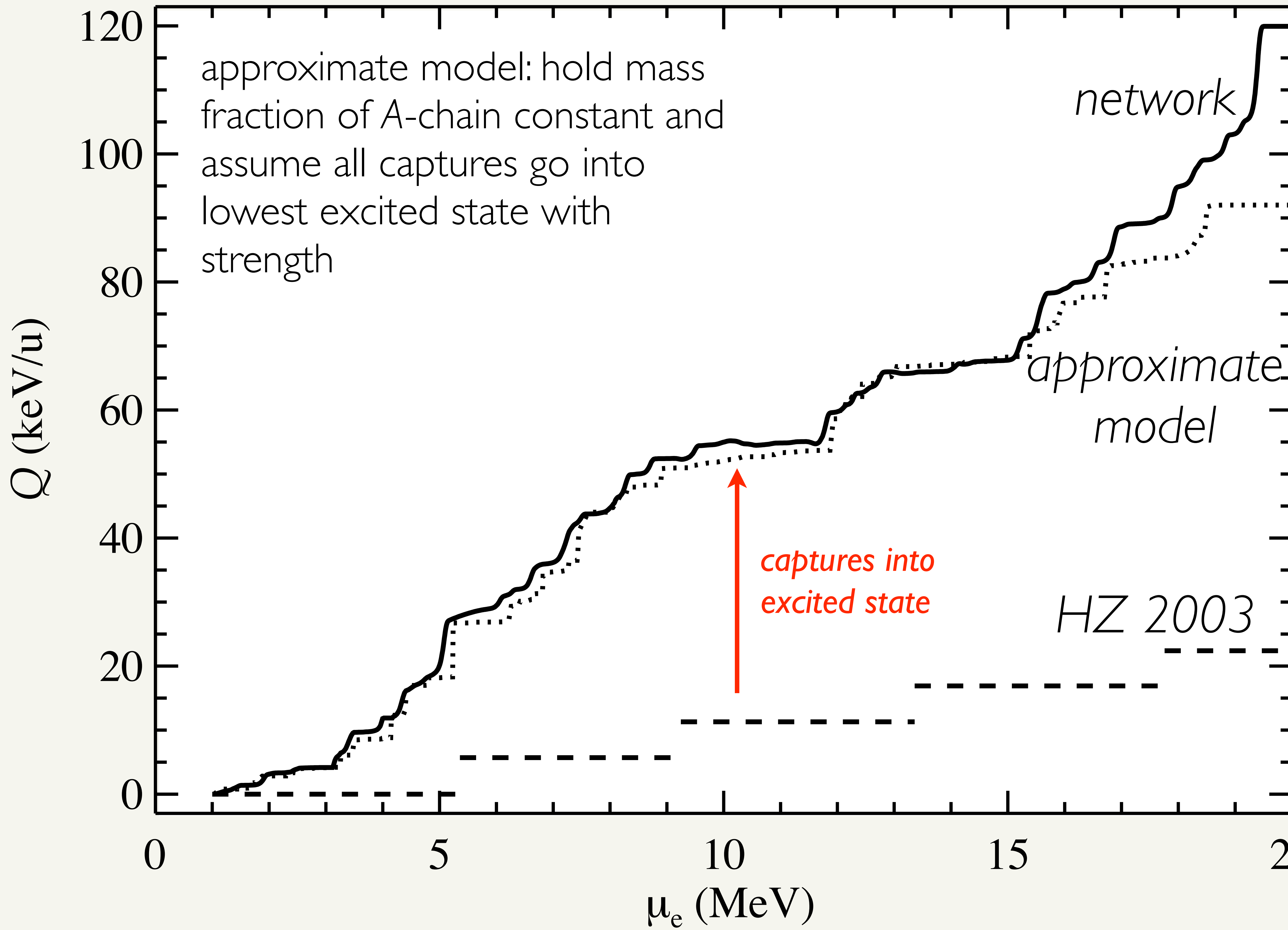
Gupta et al. 07

Accretion pushes material deeper into crust, where the pressure is

$$P = \frac{1}{4} n_e \mu_e \propto \mu_e^4.$$



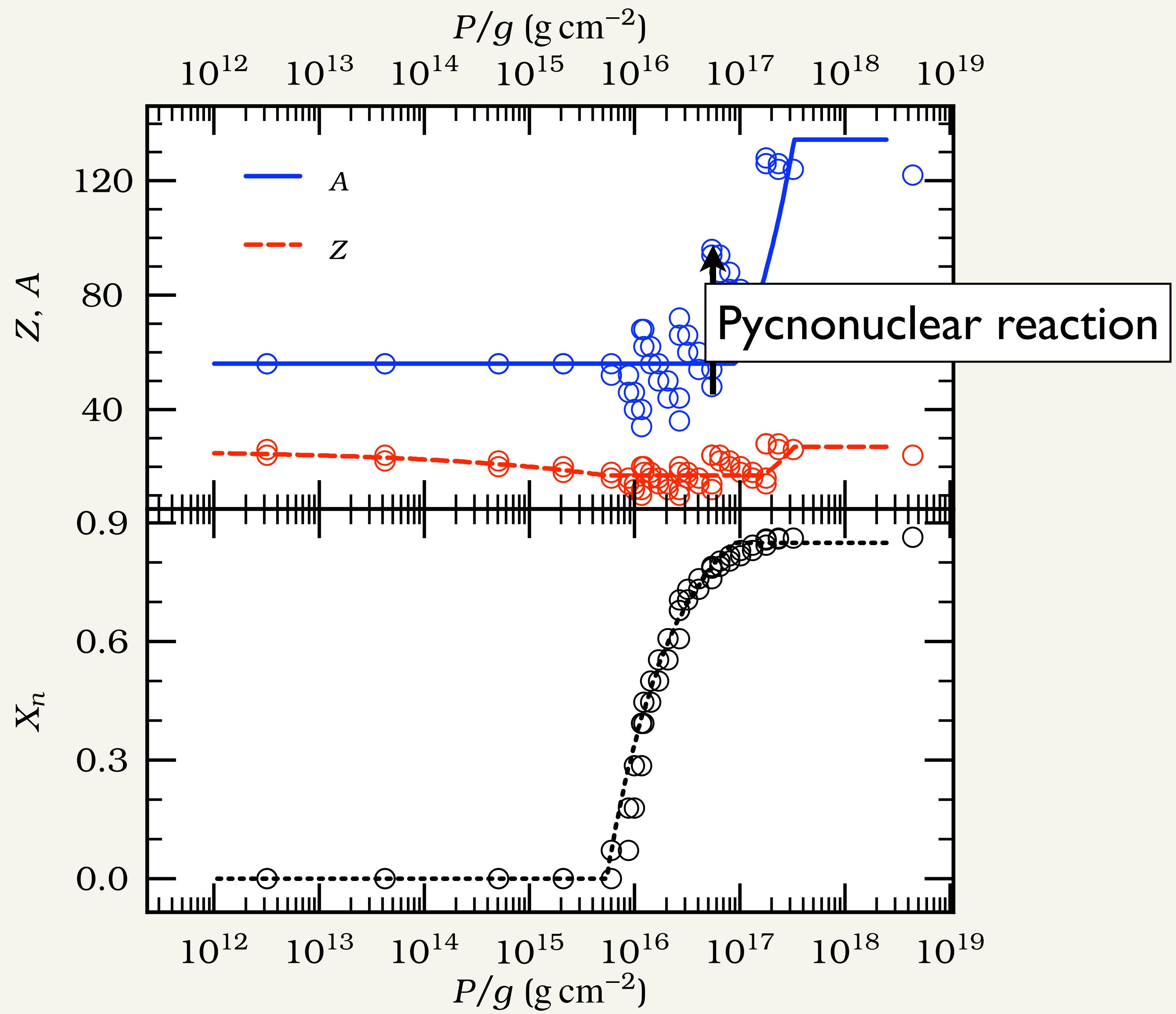
heating

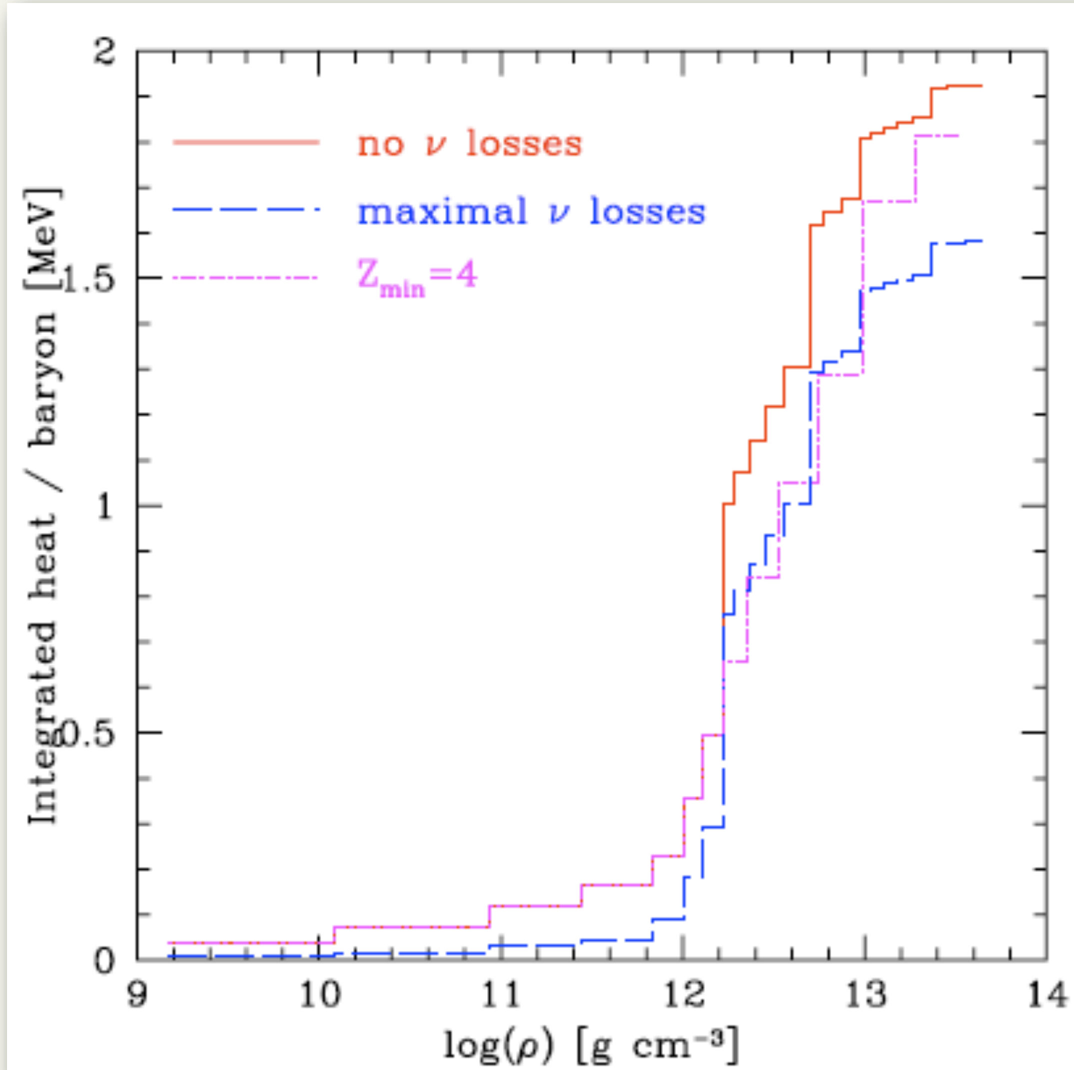


approximate model: hold mass fraction of A-chain constant and assume all captures go into lowest excited state with strength
network
approximate model
captures into excited state
HZ 2003
Q (keV/u)
μe (MeV)
0
20
40
60
80
100
120
0
5
10
15
20

Crust composition

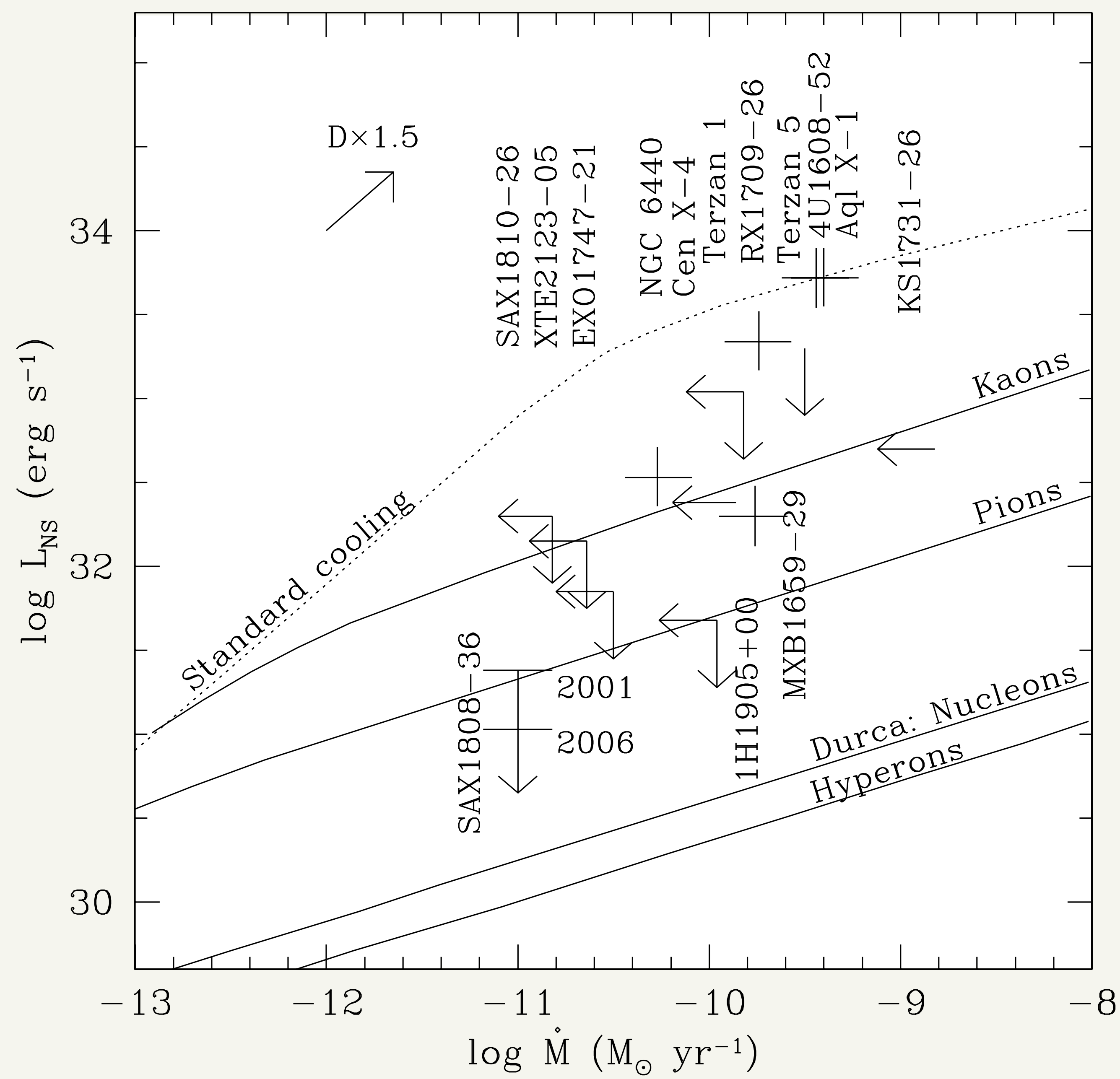
Haensel & Zdunik 08





Integrated heating, HZ08

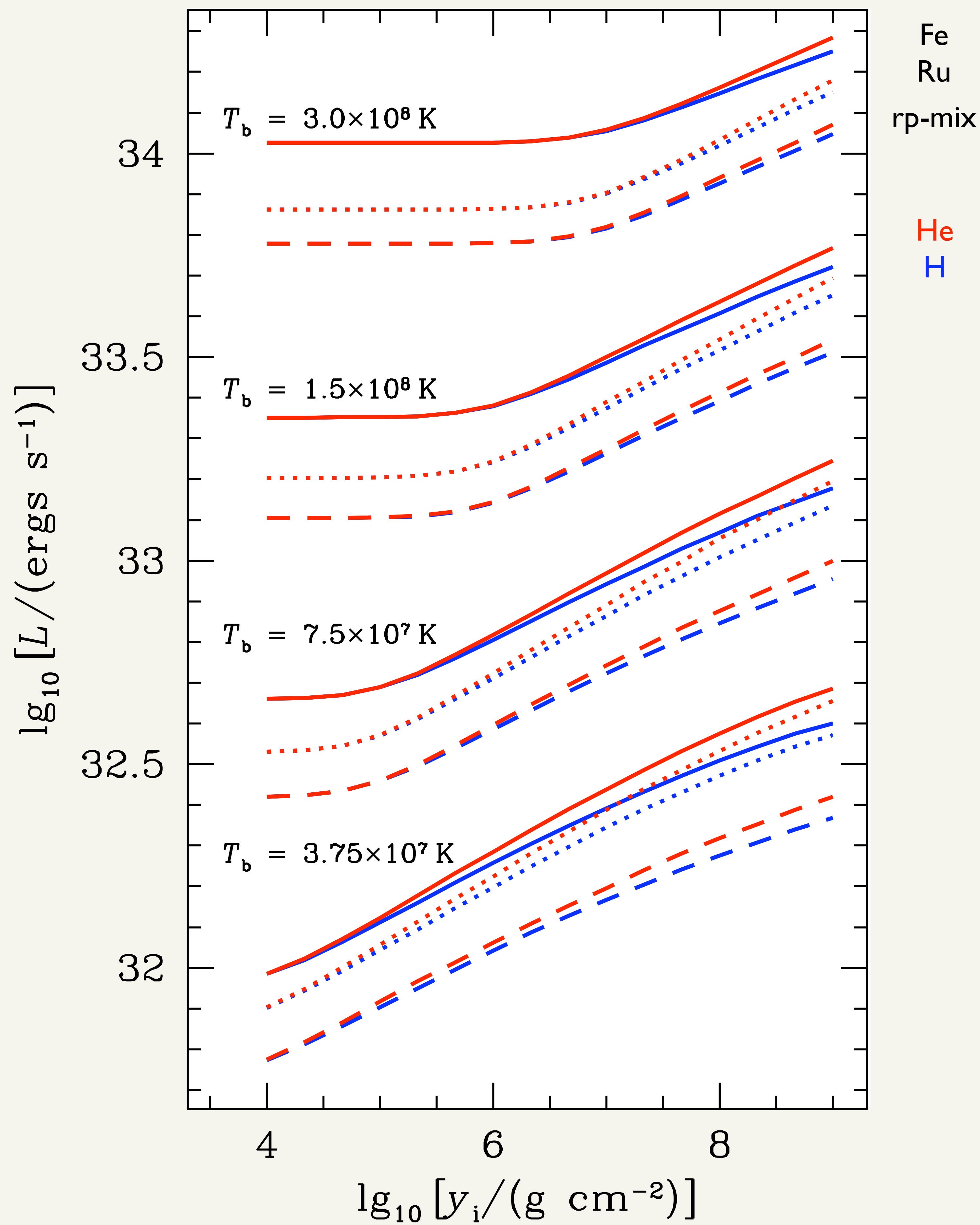
Heinke et al. 07



Observations of deep crustal heating

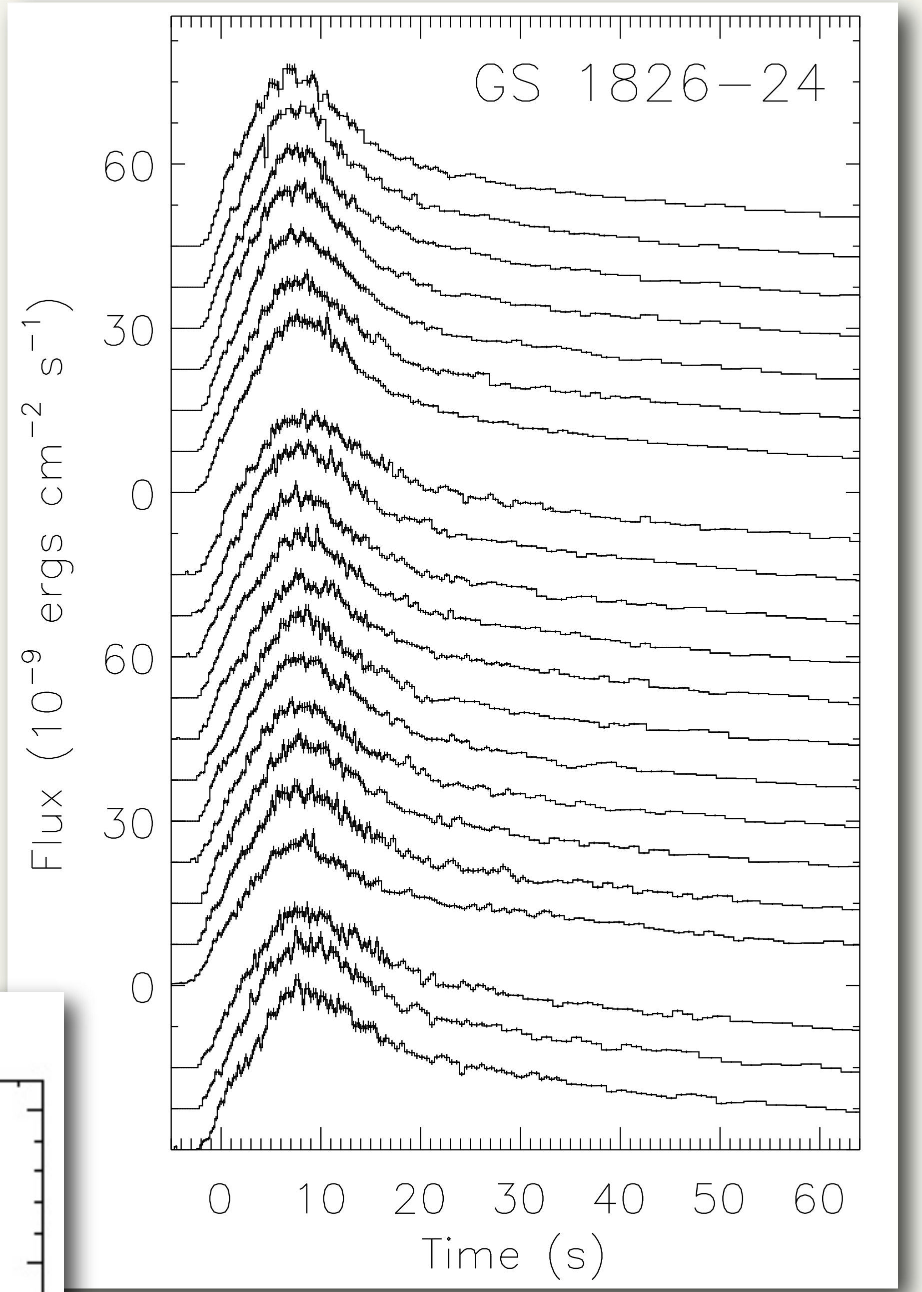
Effect of heat blanketing enveope

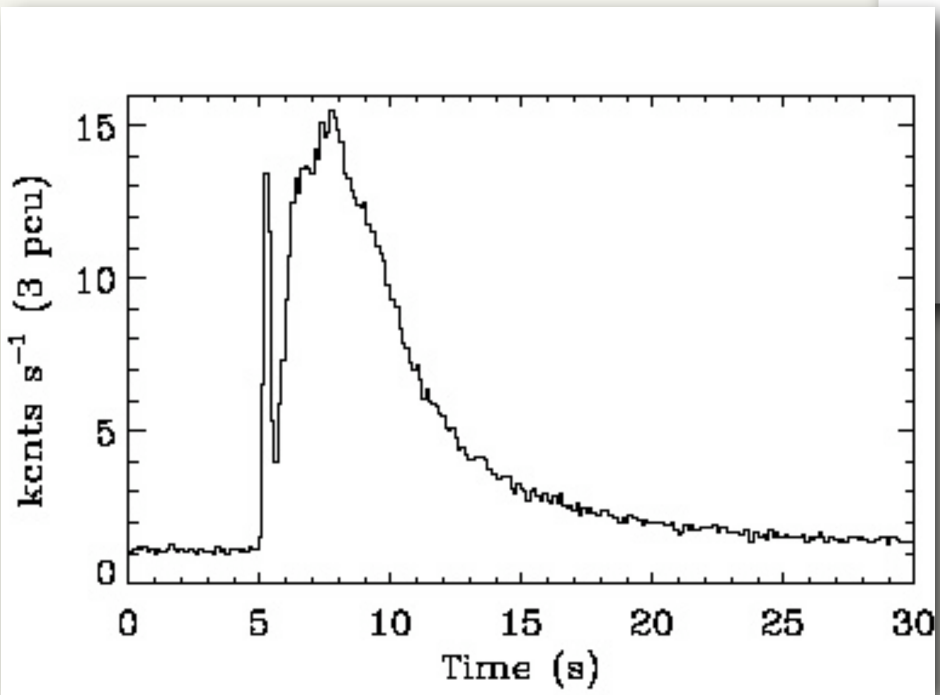
Gudmundson et al. 83, Potekhin et al. 98; Brown et al. 02



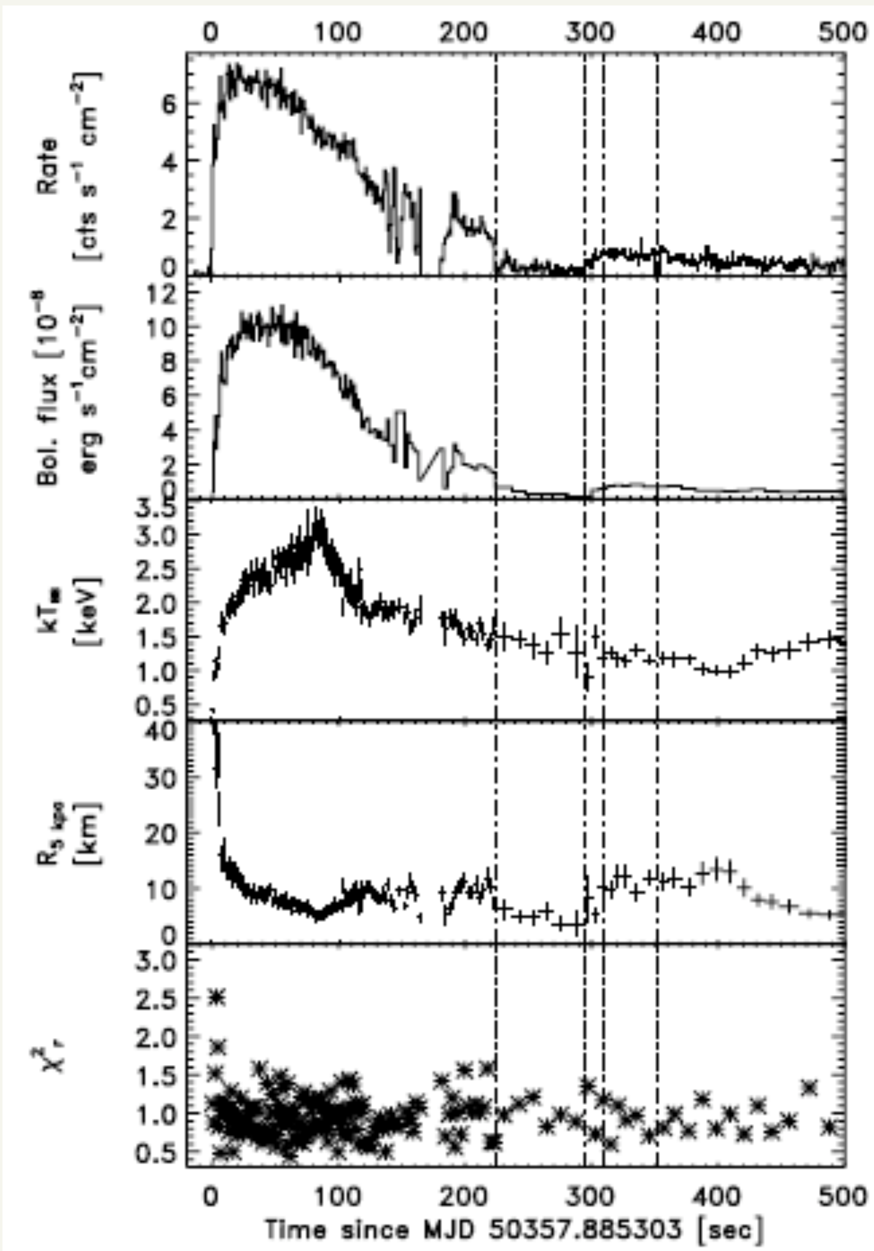
Effect on unstable burning in envelope

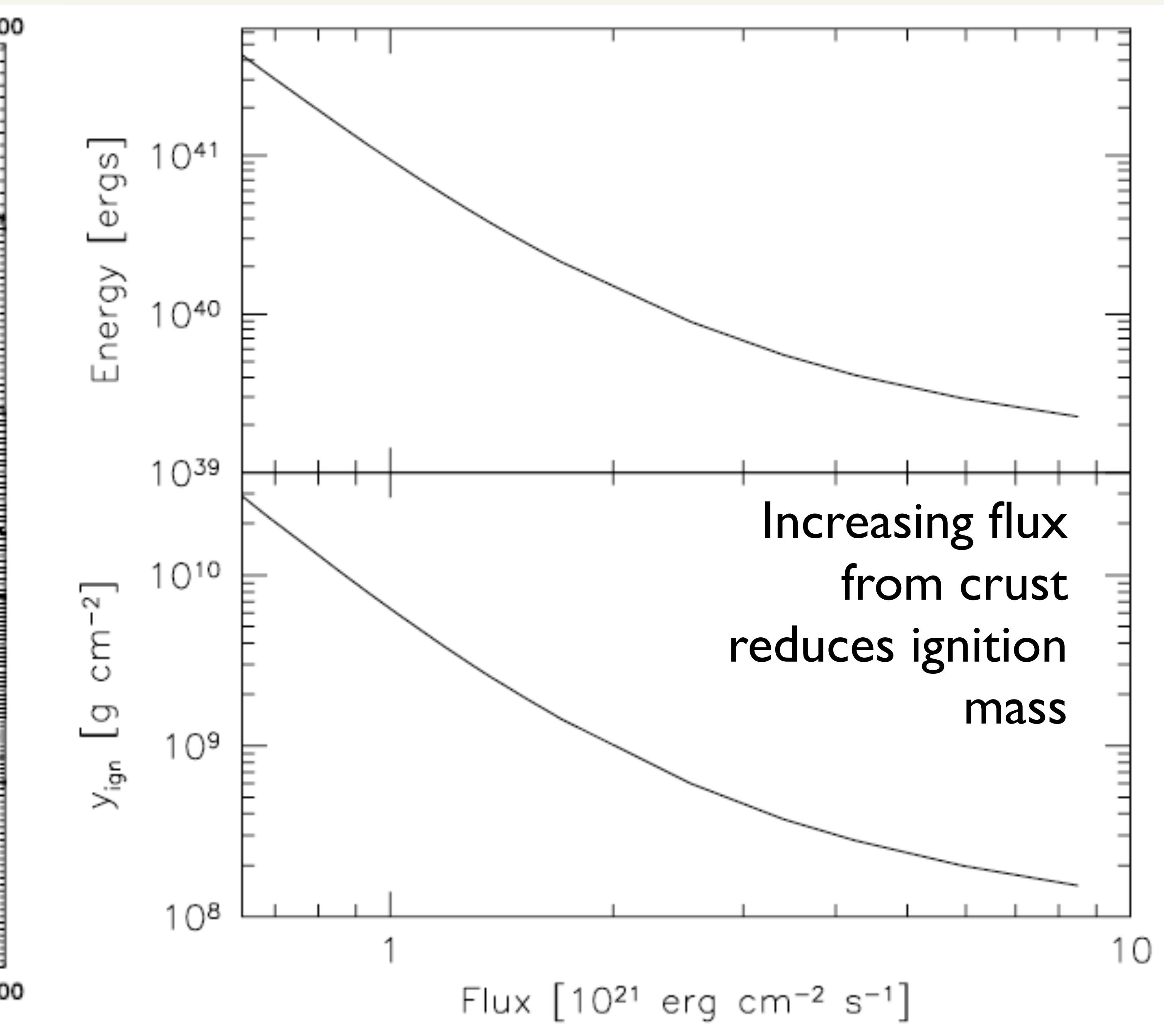
Strohmayer, Galloway et al.





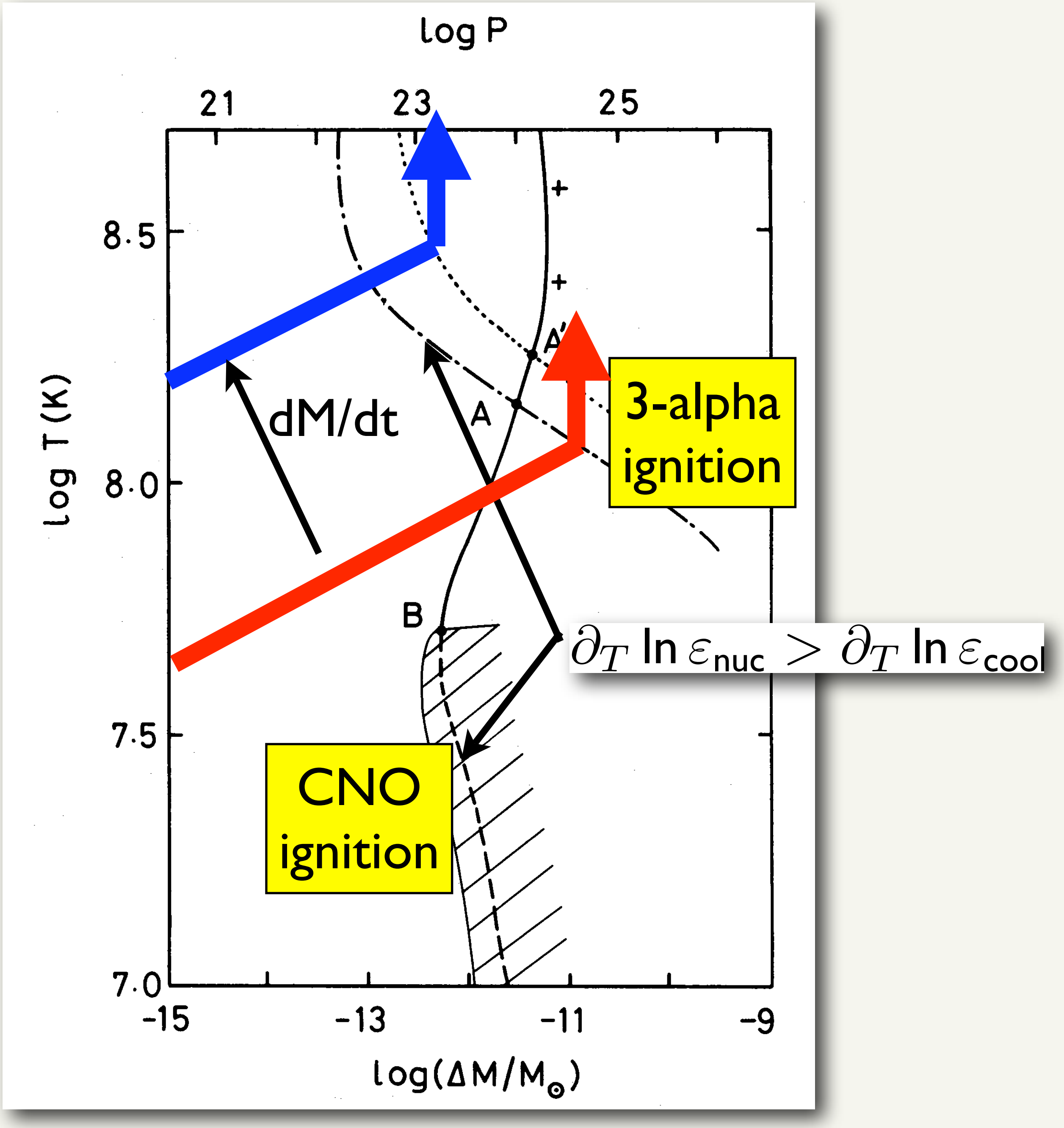
Long (He) X-ray bursts in 2S 0918–549 (in ‘t Zand 05)





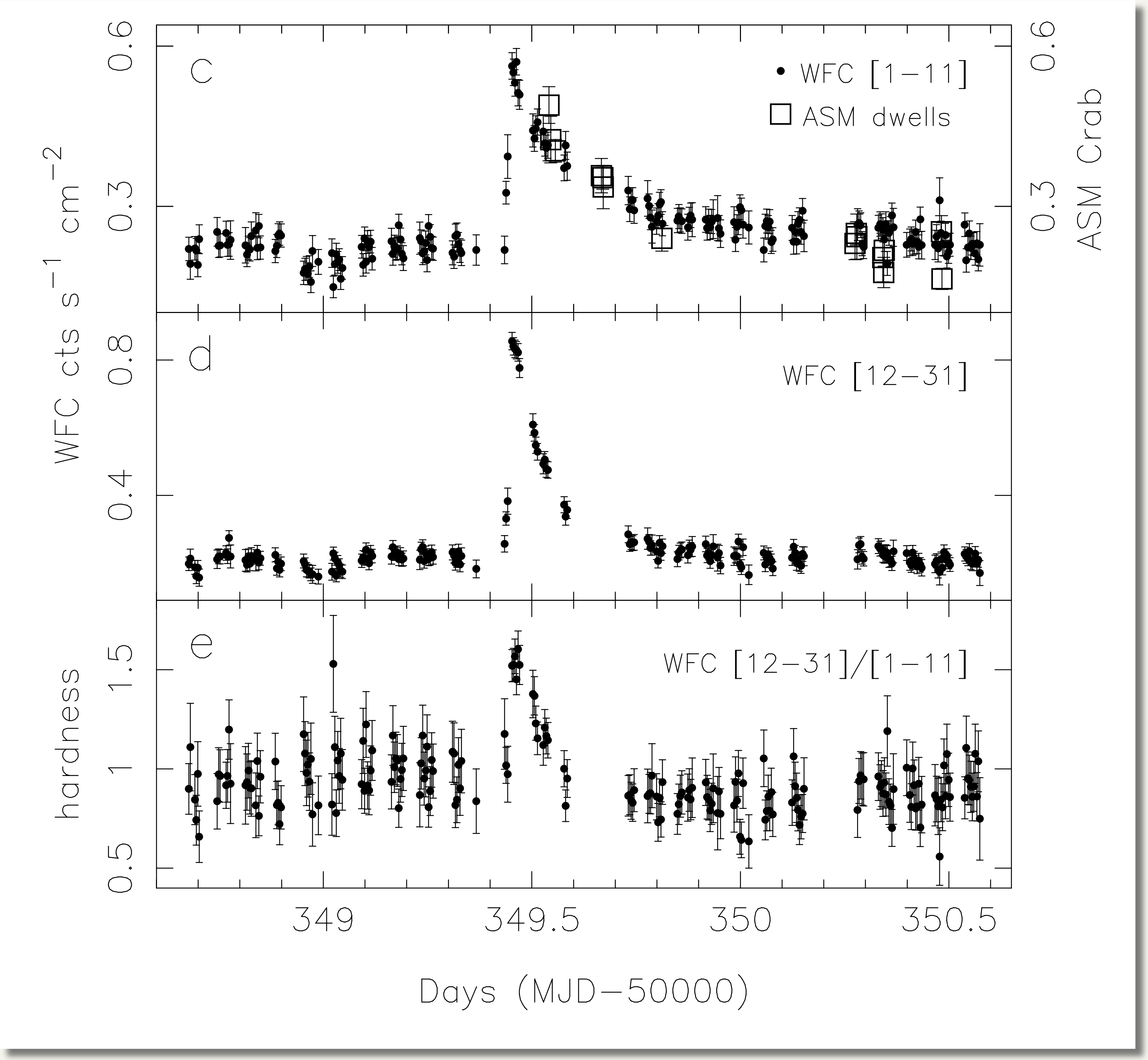
X-ray bursts

- Consumption of H regulated by β-decay of ^{14}O, ^{15}O
- time to deplete H is ≈18 hr
- temperature set by ≈7 MeV/u from H burning
- sensitive to temperature in deep crust if pure He accreted, or complete H burning prior to He ignition (as in SAX J1808.4–268; Galloway & Cumming 06)



Fujimoto et al. 1981

KS 1731–260 superburst (Kuulkers 2002)



- About 10^3 more energetic than type I XRB
- cooling time ~ hrs
- recurrence time ~ yrs

Determining ignition mass

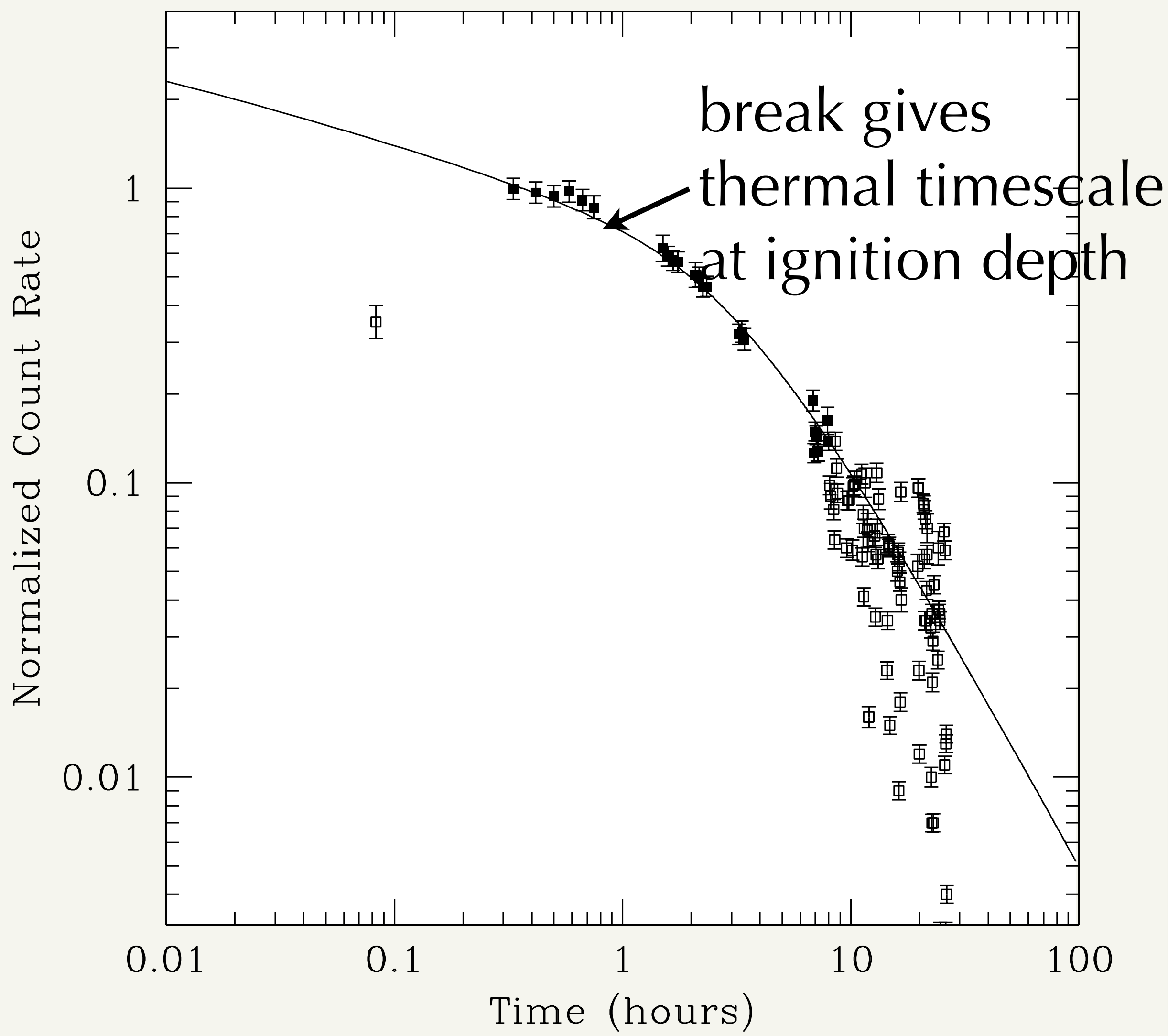


FIG. 5.— Fitted lightcurve for KS 1731-260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.

- Can't use total energetics because of significant neutrino emission; (Strohmayer & Brown 02, Schatz et al. 03)
- Cooling follows broken power-law, with change of slope at thermal timescale at ignition depth (Cumming et al. 07)

TABLE 1
FITS TO SUPERBURST LIGHTCURVES

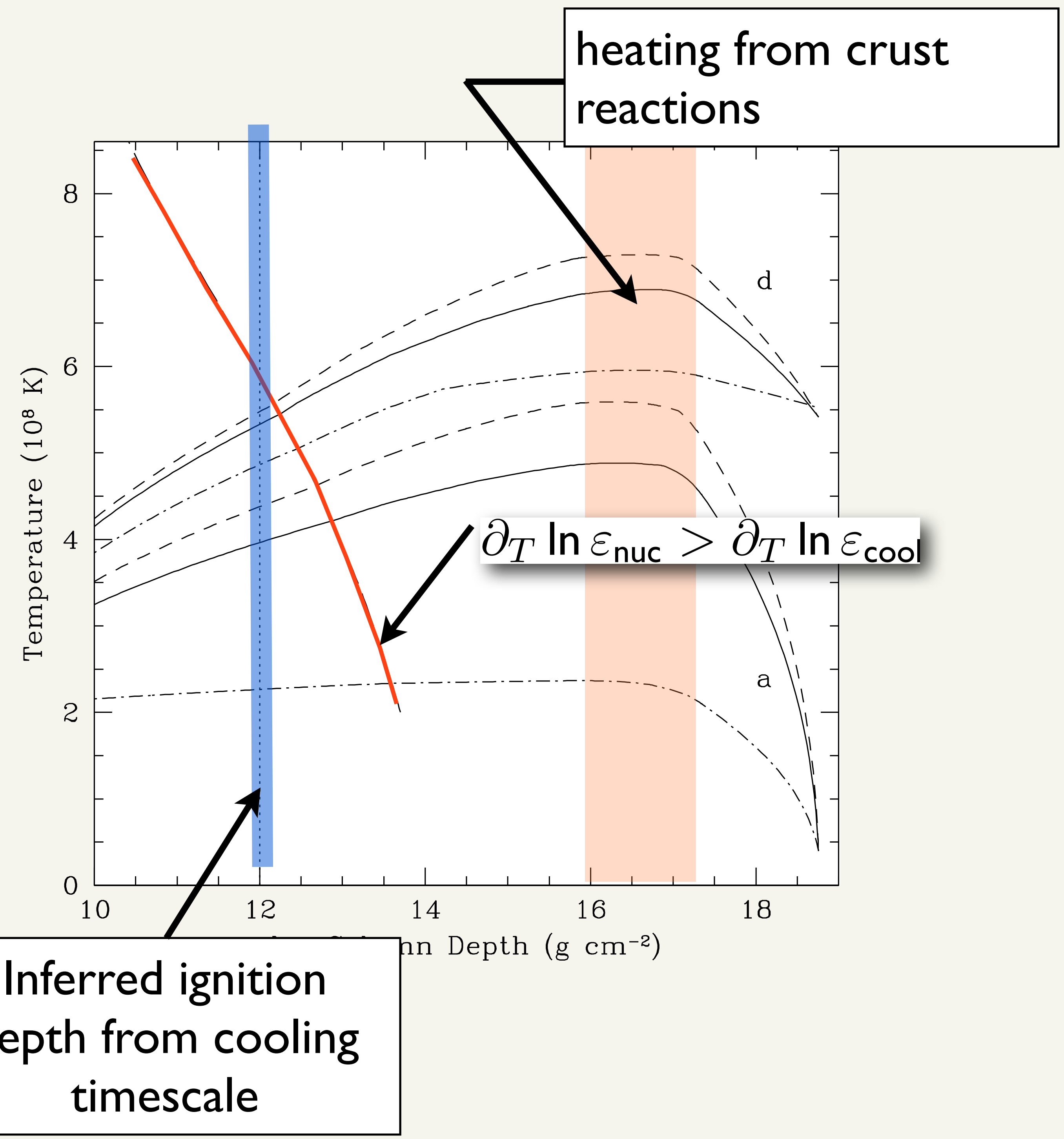
Source	f_{peak}[a]	d/R[b]	E_{17}[c]	y_{12}[c]
4U 1254-690	0.22	13	1.5	2.7
4U 1735-444	1.5	8	2.6	1.3
KS 1731-260	2.4	4.5	1.9	1.0
GX 17+2 burst 2	0.8	8	1.8	0.64
Ser X-1	1.9	6	2.3	0.55
4U 1636-54	2.4	5.9	2.6	0.48

[a] Observed peak flux in units of 10^{-8} erg cm^{-2} s^{-1}.
[b] Adopted distance in units of kpc/10 km.
[c] The fitted parameters scale roughly as $E_{17} \propto (d/R)^{8/7}$ and $y_{12} \propto (d/R)^{10/7}$ (see text). For a 50% distance uncertainty, the uncertainties in E_{17} and y_{12} are 60% and 70% respectively (see also Fig. 4).

From Cumming et al. 07

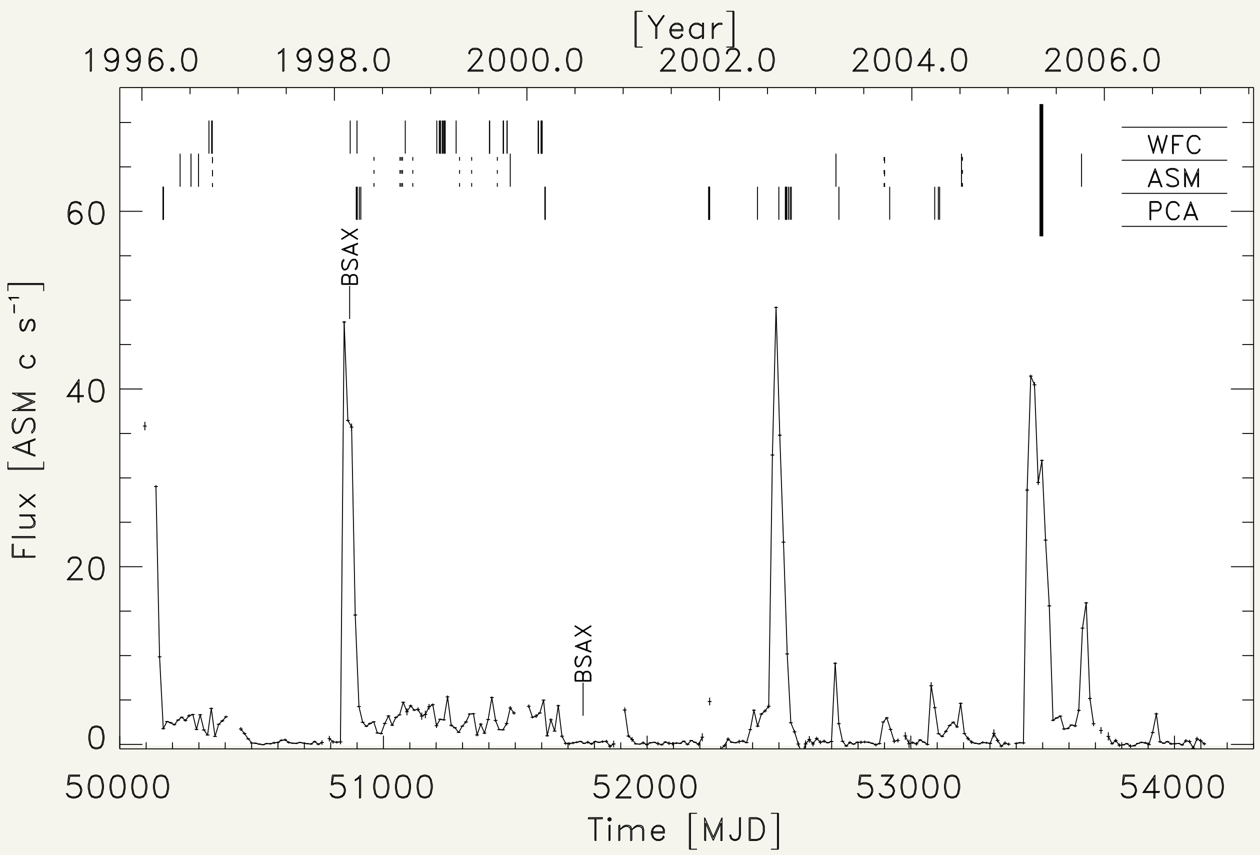
Superburst ignition

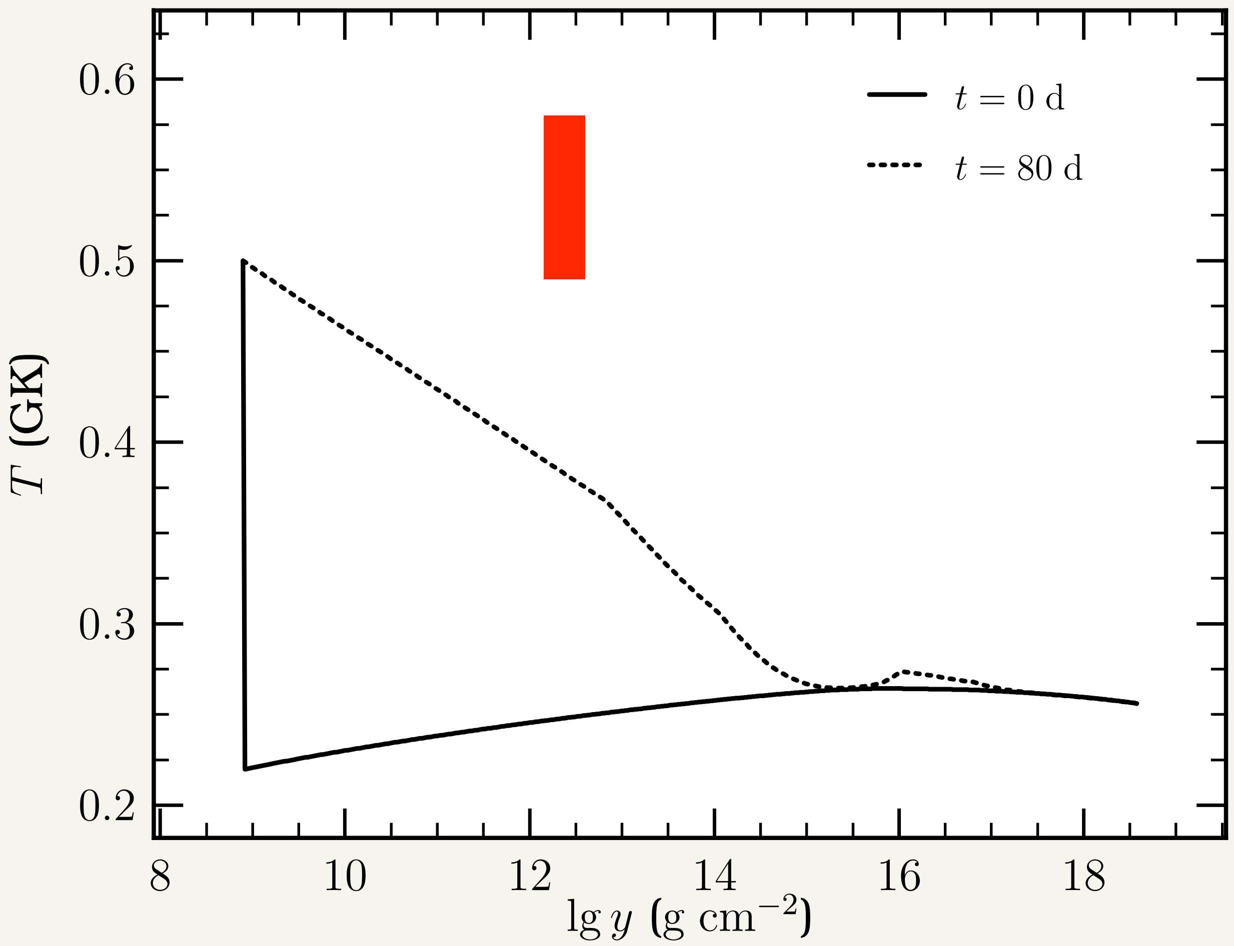
- ^{12}C likely cause of superbursts (Cumming & Bildsten 01, Strohmayer & Brown 02)
- Hot crust required to match inferred ignition depth (Brown 04; Cooper & Narayan 05; Cumming et al. 06)
    - No enhanced cooling
    - low thermal conductivity (impure, amorphous crust)



Plot from Cumming et al. 06

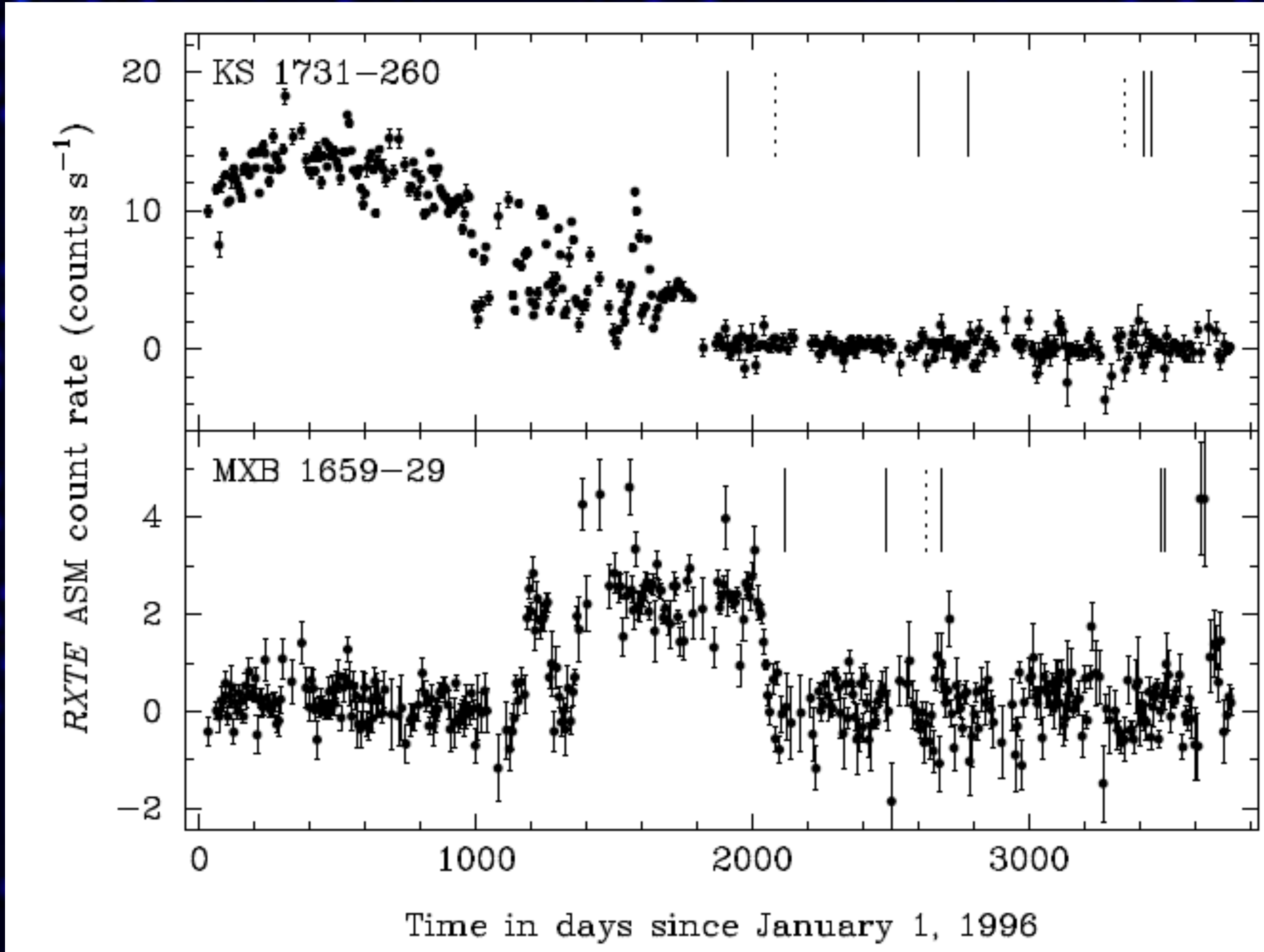
Keek et al. 08



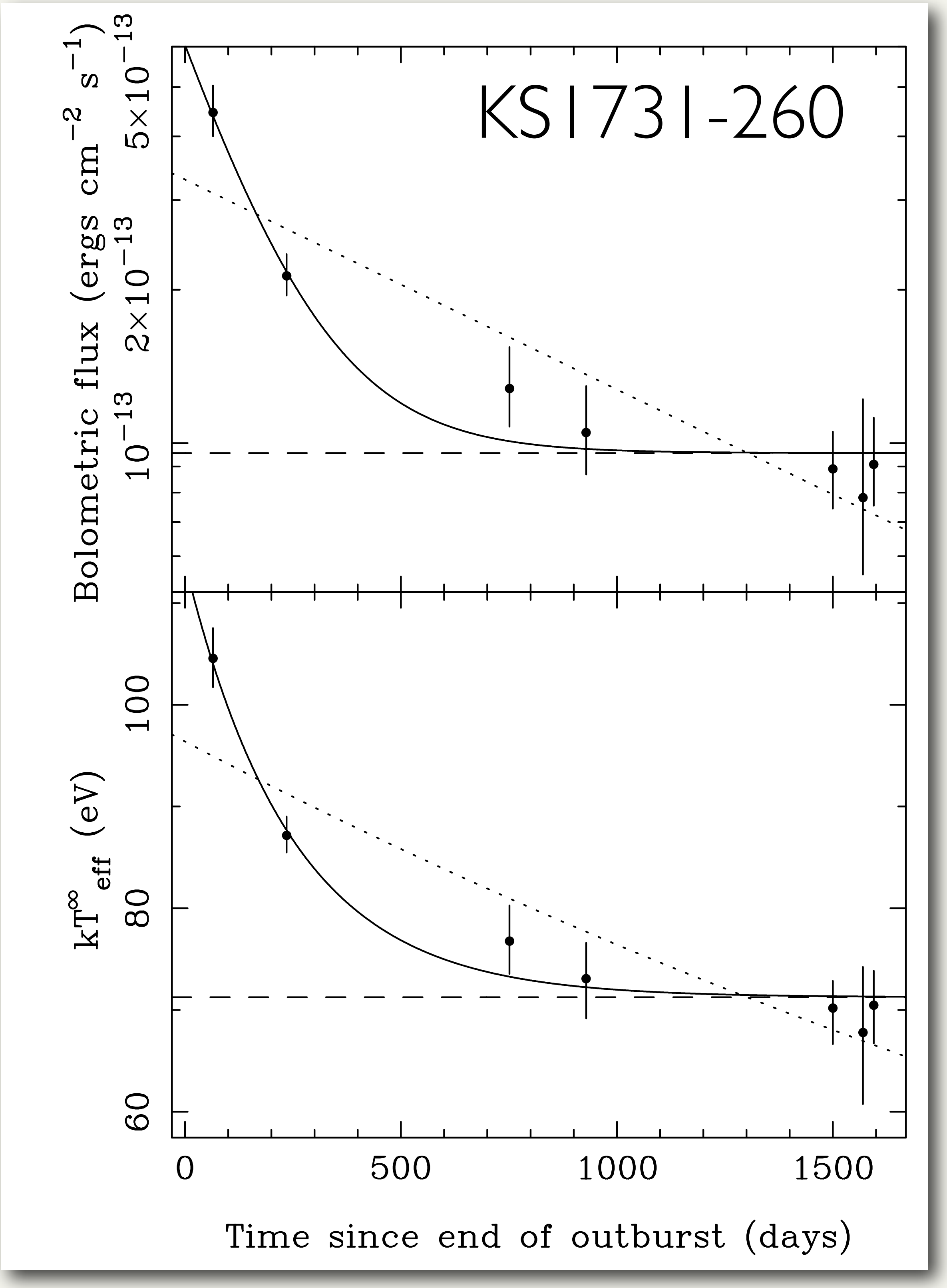


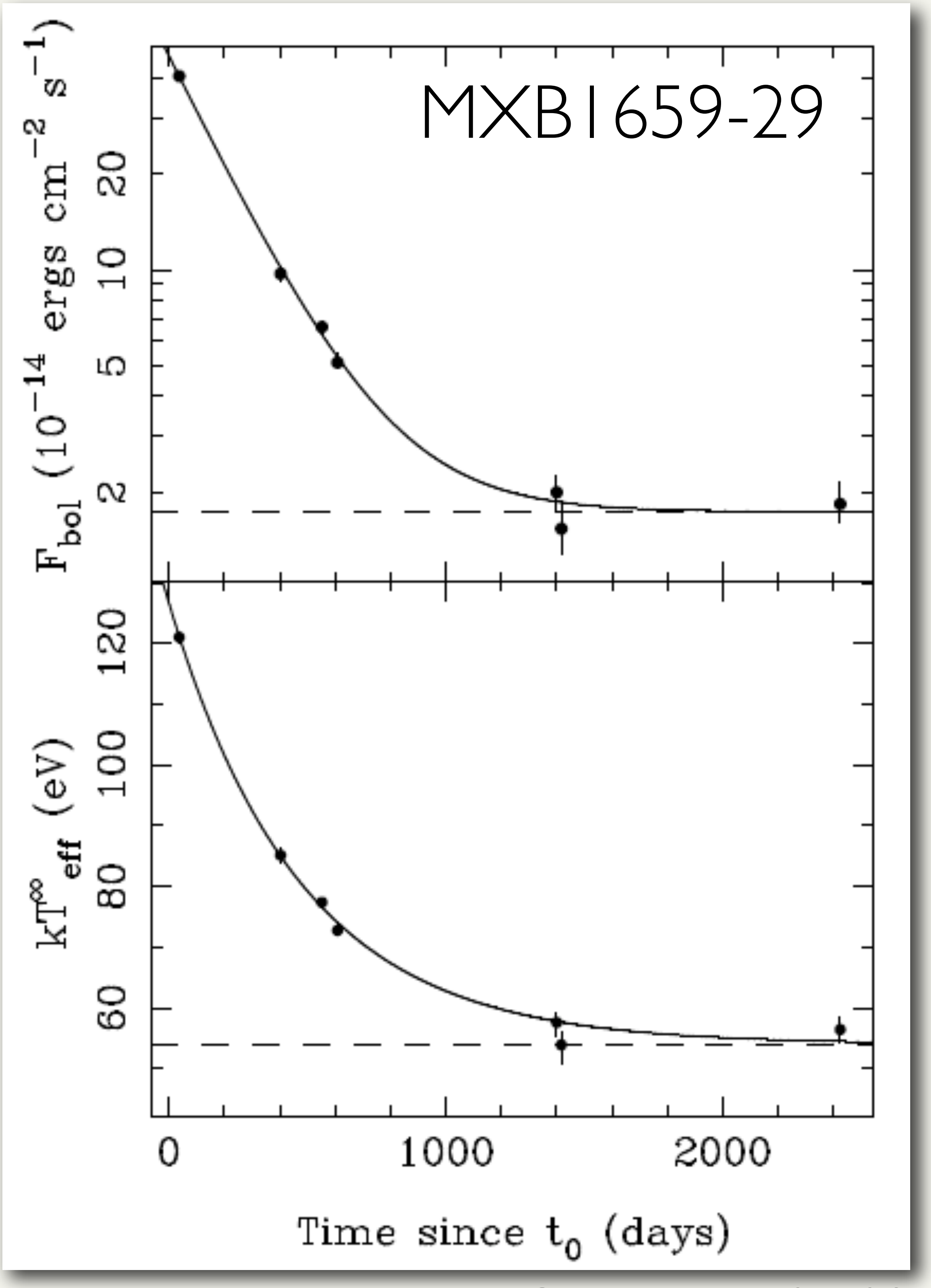
1608–522 superburst

Rutledge et al. 02 suggested looking for post-outburst thermal relaxation of crust for transients with extended outbursts



quiescent lightcurves



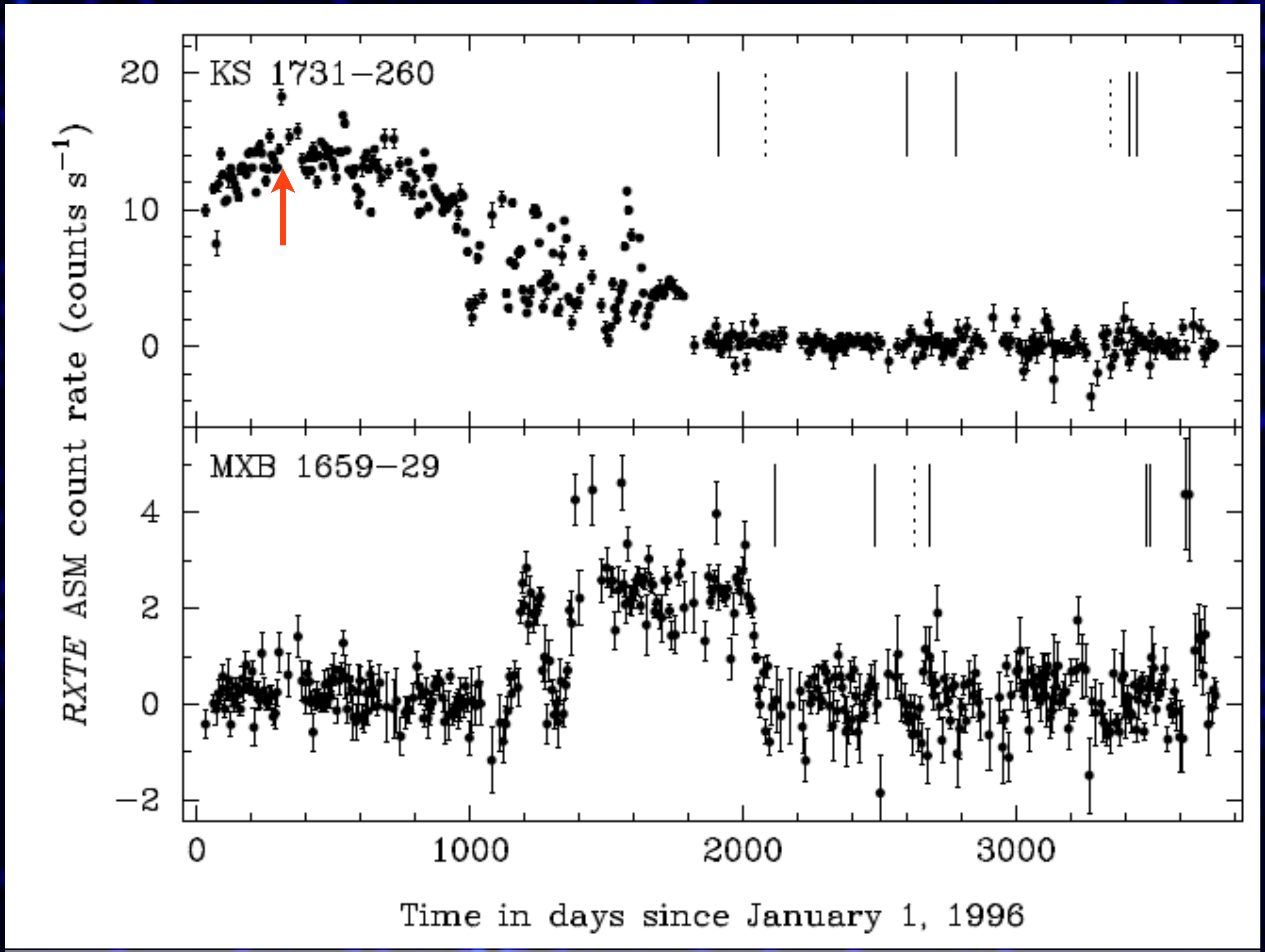


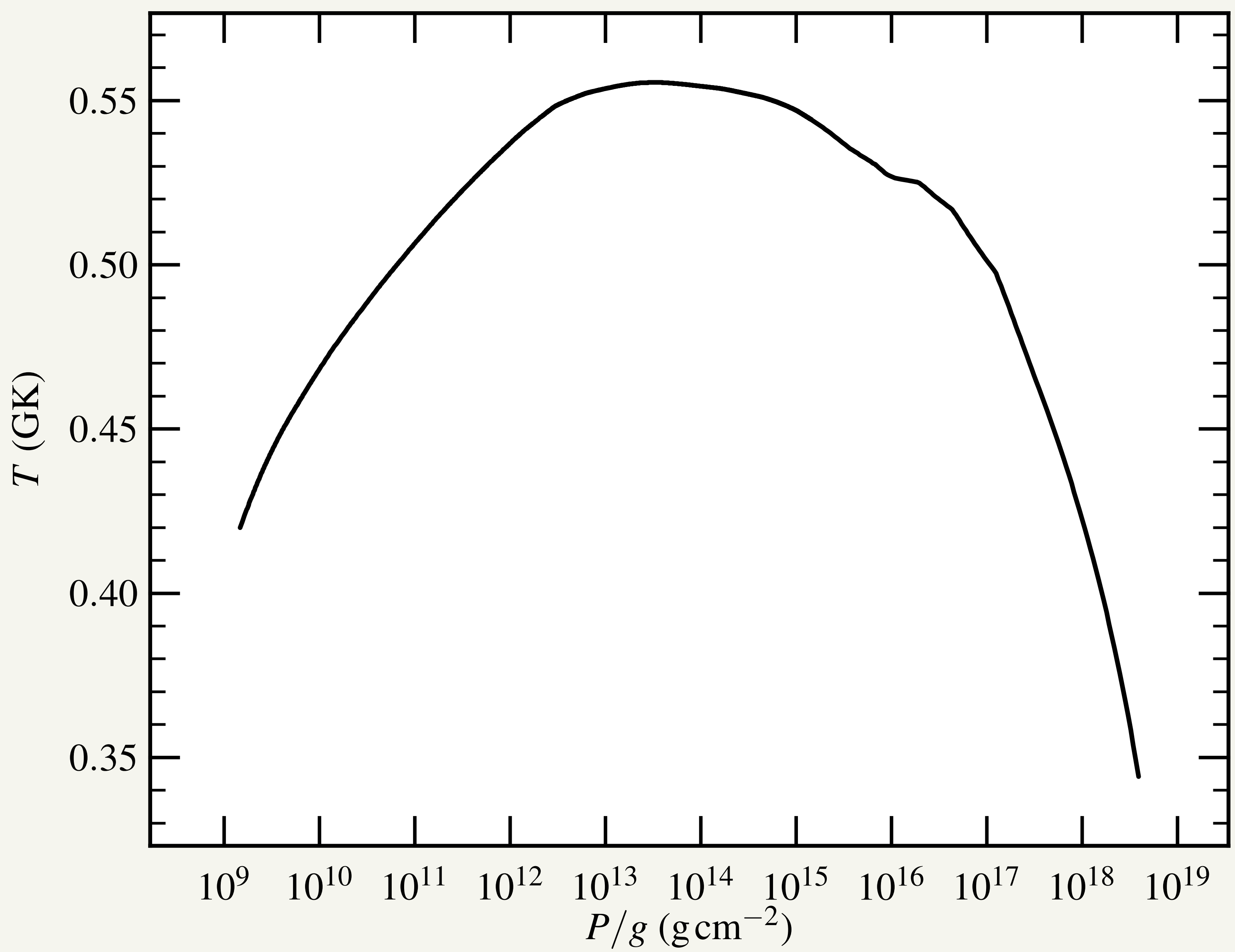
Cackett et al. 06, 08

Rutledge et al. 02 suggested looking for post-outburst thermal relaxation of crust

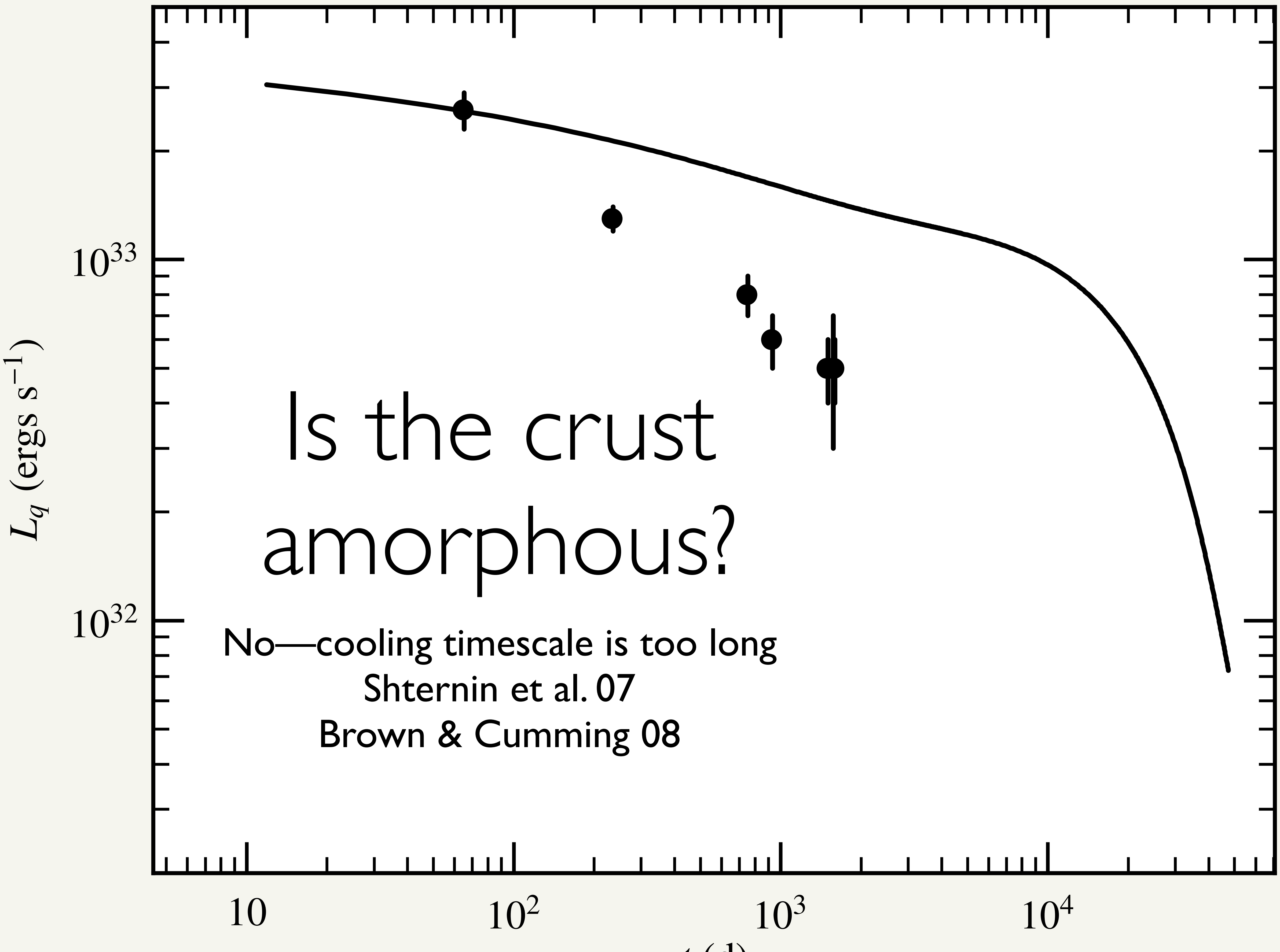
Observations (Wijnands et al., Cackett et al.) detected this cooling

Shternin et al. 2007 fit KS 1731 lightcurve, suggest crust has high thermal conductivity





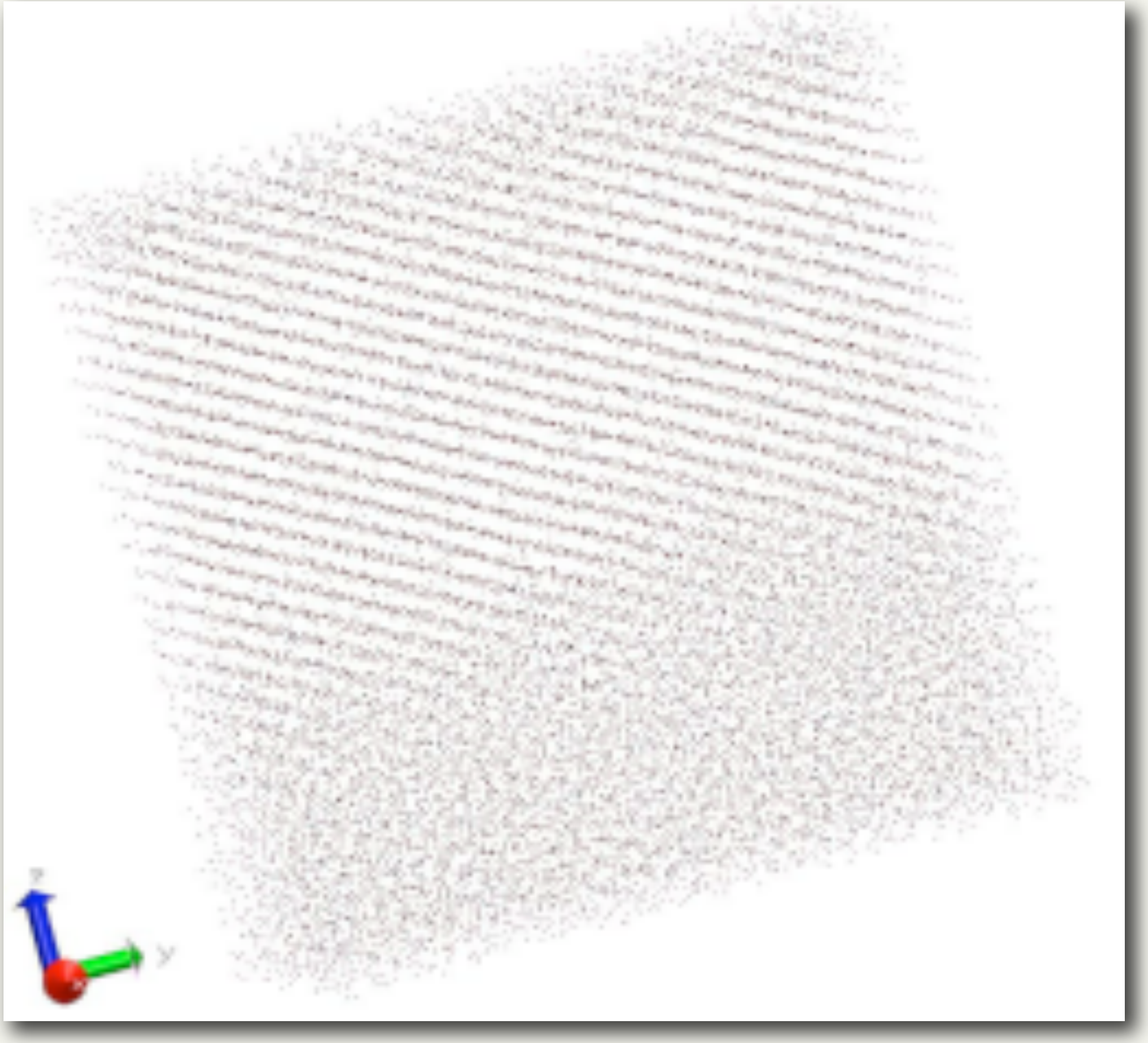
Is the crust amorphous?



Is the crust amorphous?
No—cooling timescale is too long
Shternin et al. 07
Brown & Cumming 08
L_q (ergs s^{-1})
10^{33}
10^{32}
10
10^2
10^3
10^4
t (d)

Implications

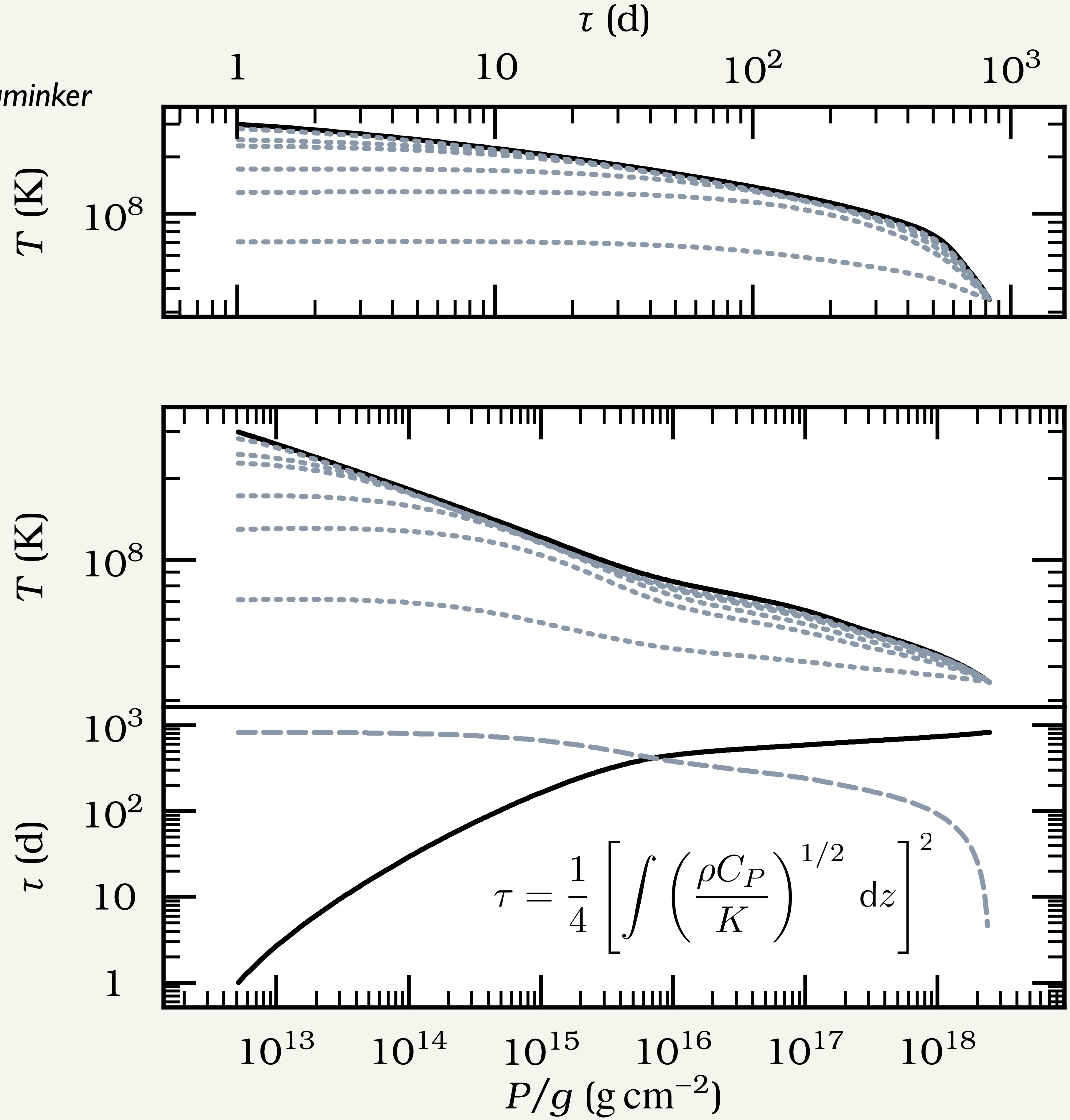
- Crust has high thermal conductivity (**not amorphous**)—agrees with MD simulations (Horowitz et al. 07, 08); cf. Shternin et al. (07)

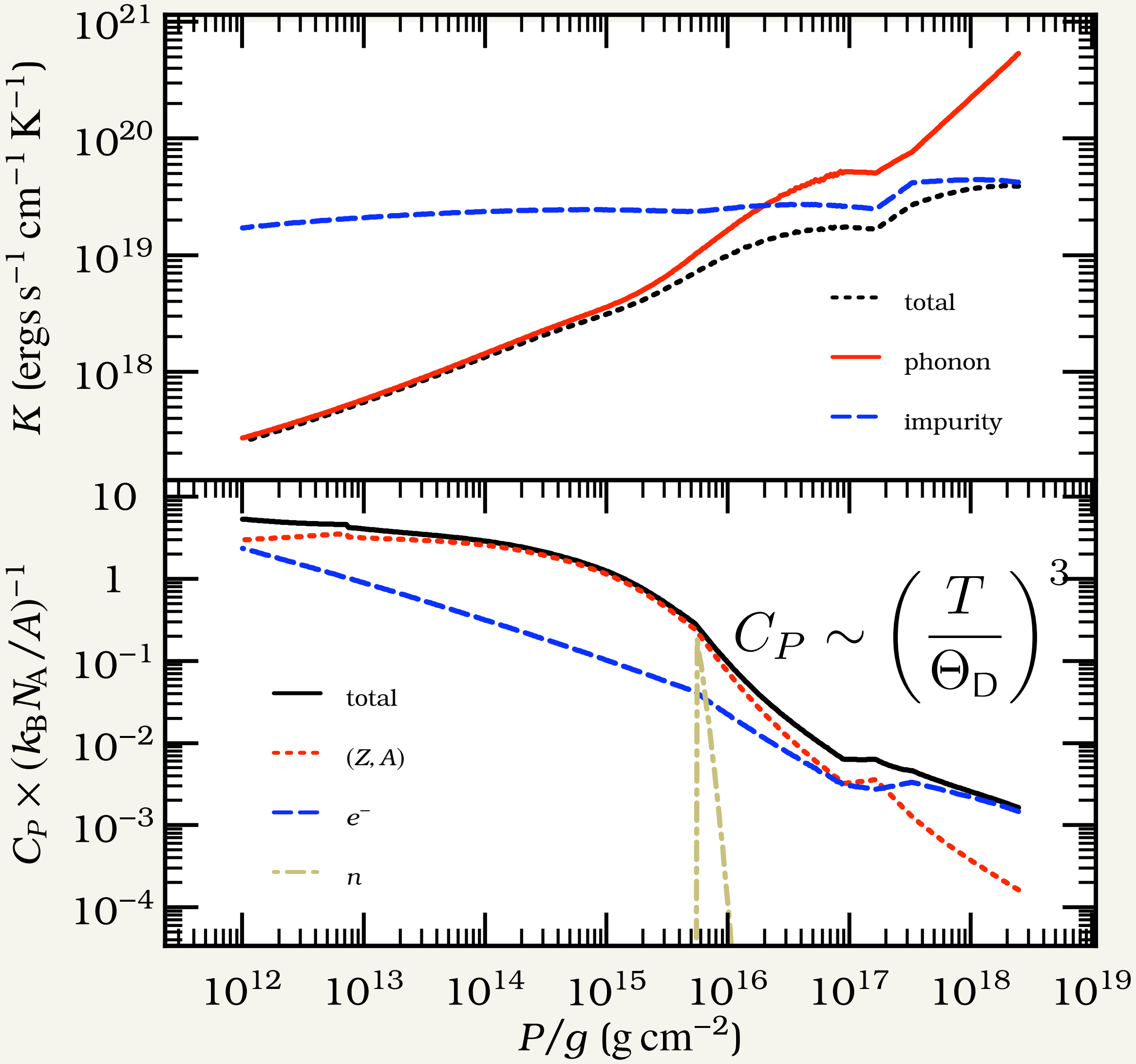


Horowitz et al. 07; note the crystalline planes!

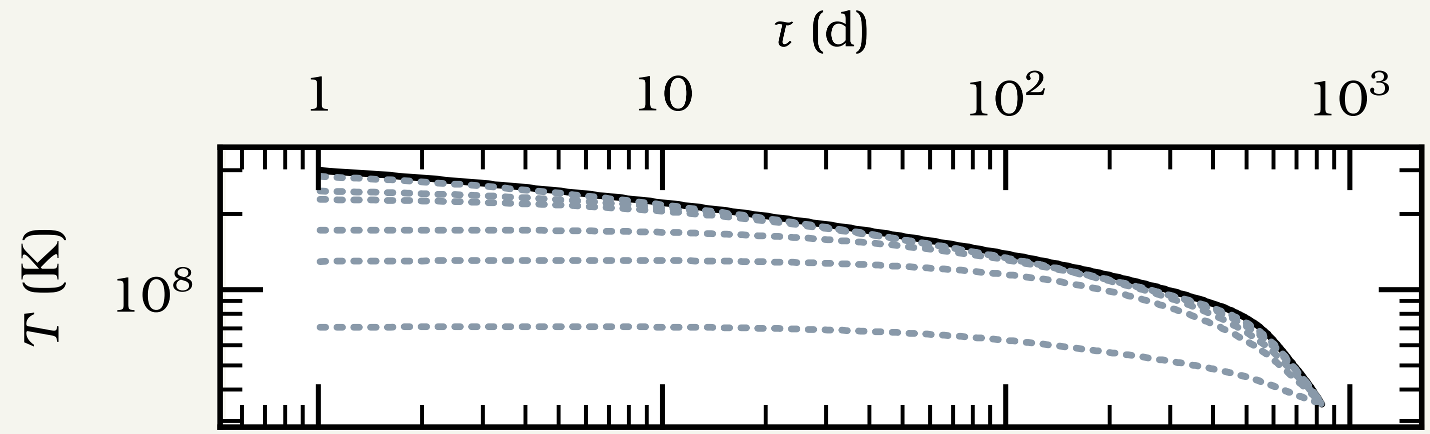
power-law cooling similar to other cases: white dwarfs in DN (Piro et al. 05) superbursts (Cumming et al. 06), magnetars (Eichler & Cheng 89, Kaminker et al. 07)

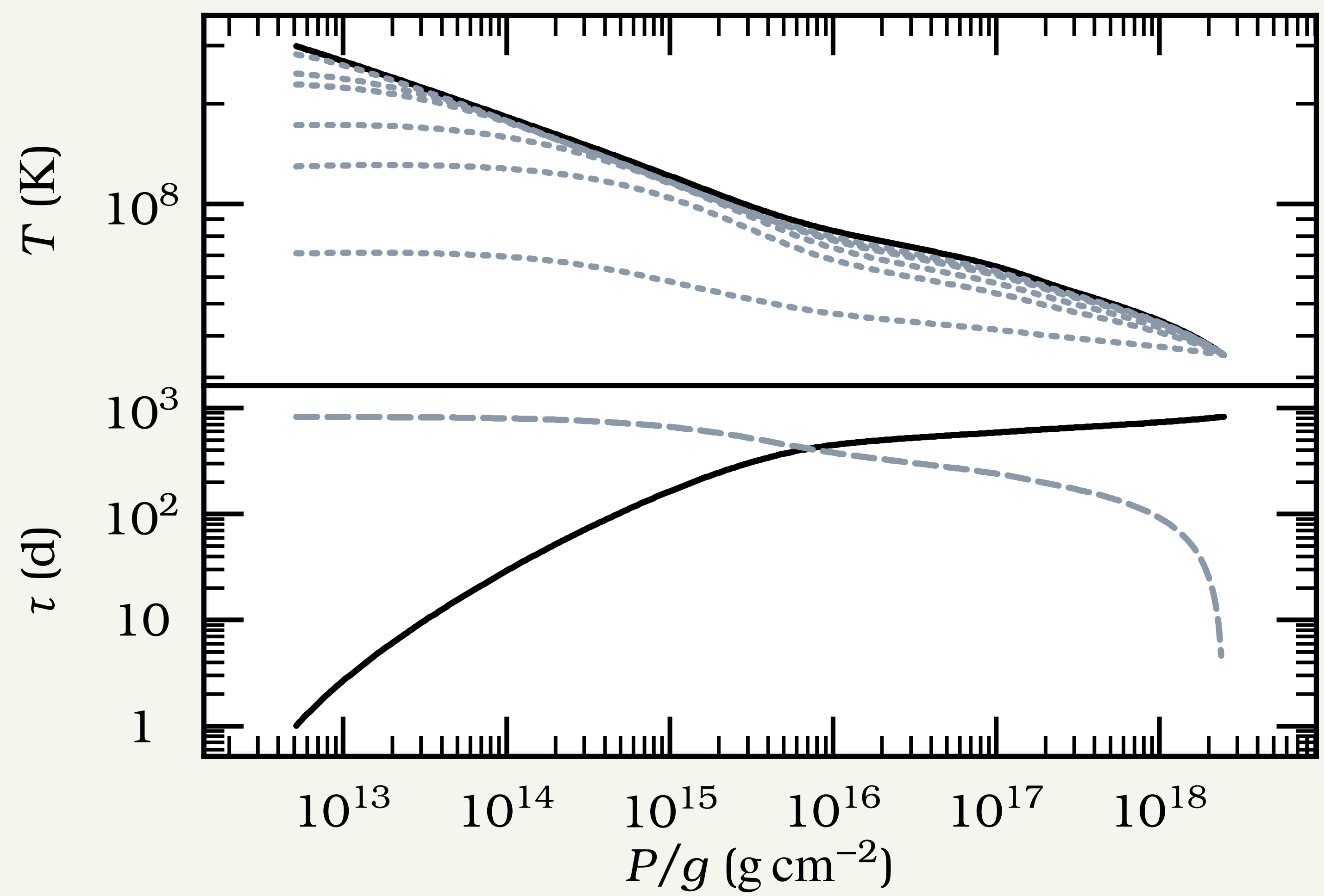
Can “invert” the lightcurve to infer the temperature profile





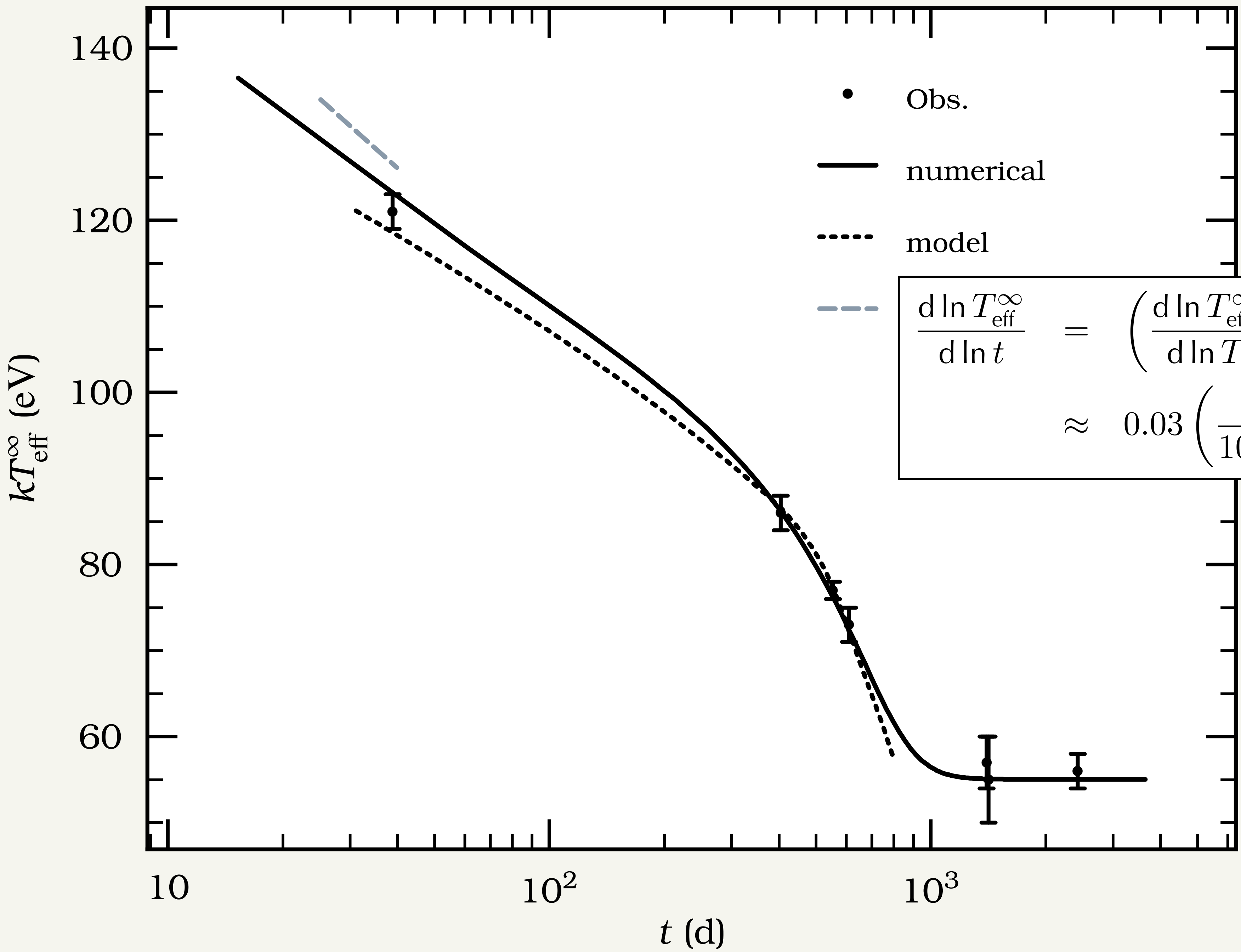
$$\tau = \frac{1}{4}\left[\int \left(\frac{\rho C_P}{K}\right)^{1/2} dz\right]^2$$





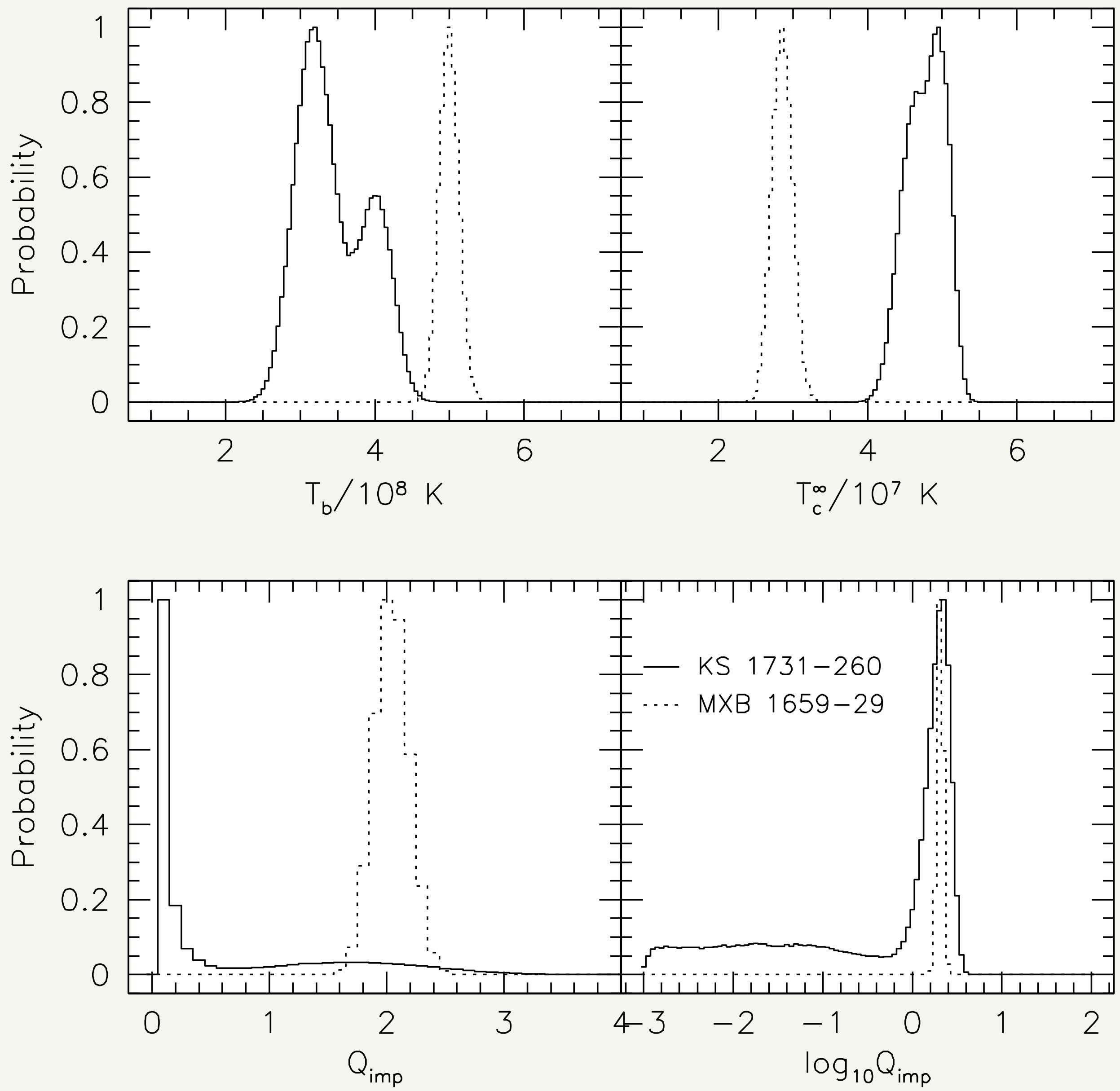
Timescale also depends on crust thickness (Lattimer et al. 94)

$$\tau \propto (\Delta r)^2 (1+z)^3$$



$$\frac{d\ln T_{\rm eff}^{\infty}}{d\ln t} = \left(\frac{d\ln T_{\rm eff}^{\infty}}{d\ln T}\right)\left(\frac{d\ln T}{d\ln y}\right)\left(\frac{d\ln y}{d\ln \tau}\right) \approx 0.03\left(\frac{F}{10^{21}\ \mathrm{ergs\,s^{-1}\,cm^{-2}}}\right),$$

Probability distribution of parameters



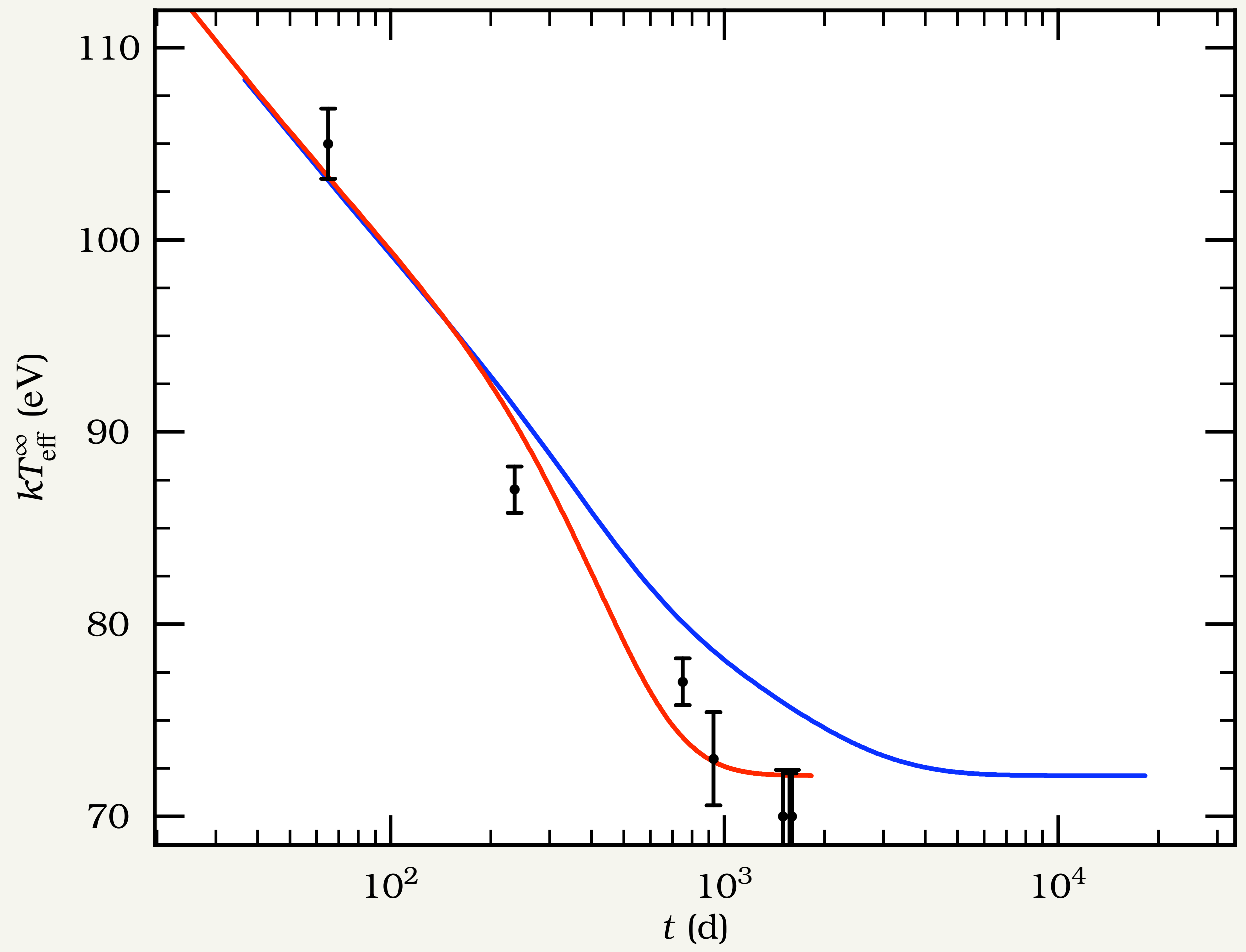
- Monte Carlo runs using simple model of lightcurve
  - 3 parameters: $Q_{\rm imp}$, $T_{\rm top}$, $T_{\rm core}$

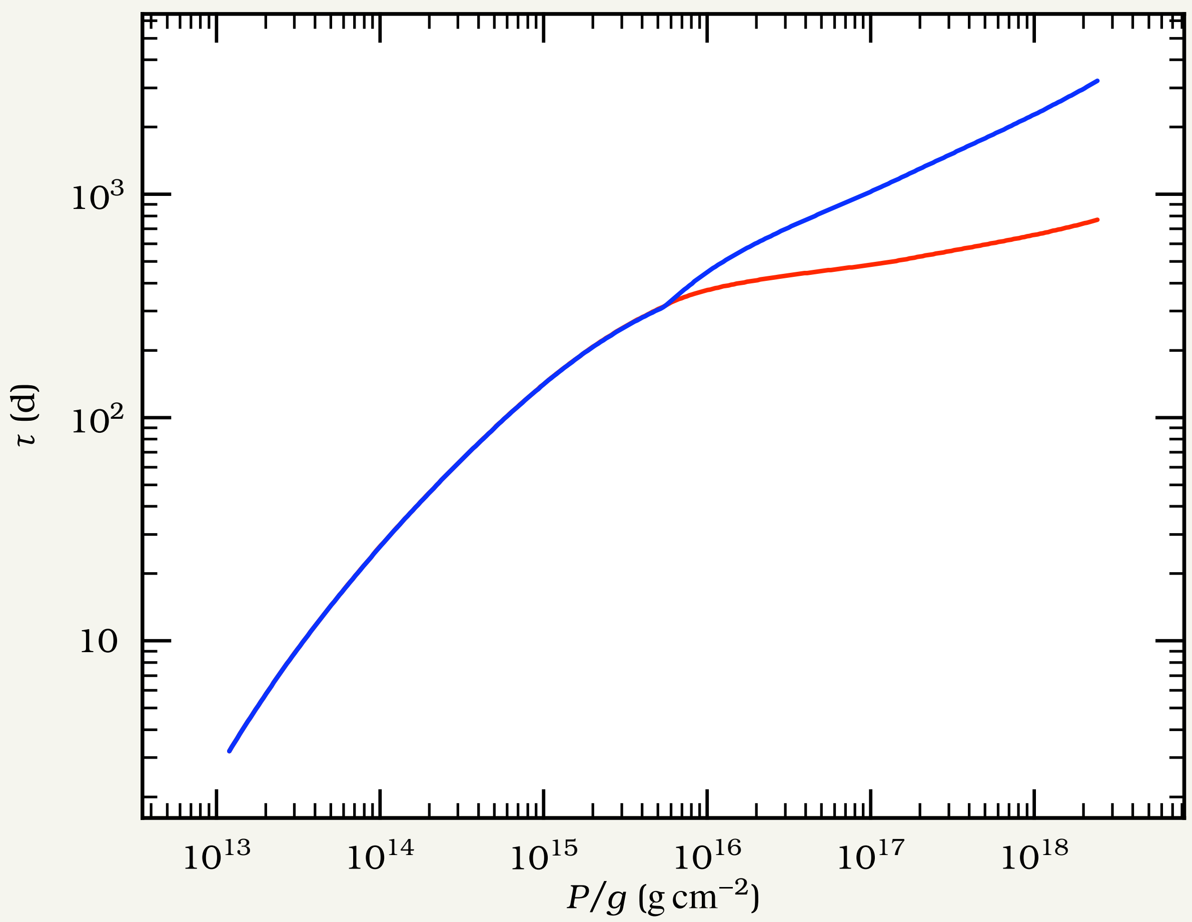
$$Q_{\rm imp} \equiv n_{\rm ion}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2 \lesssim 10$$

- Confirm with numerical cooling calculations

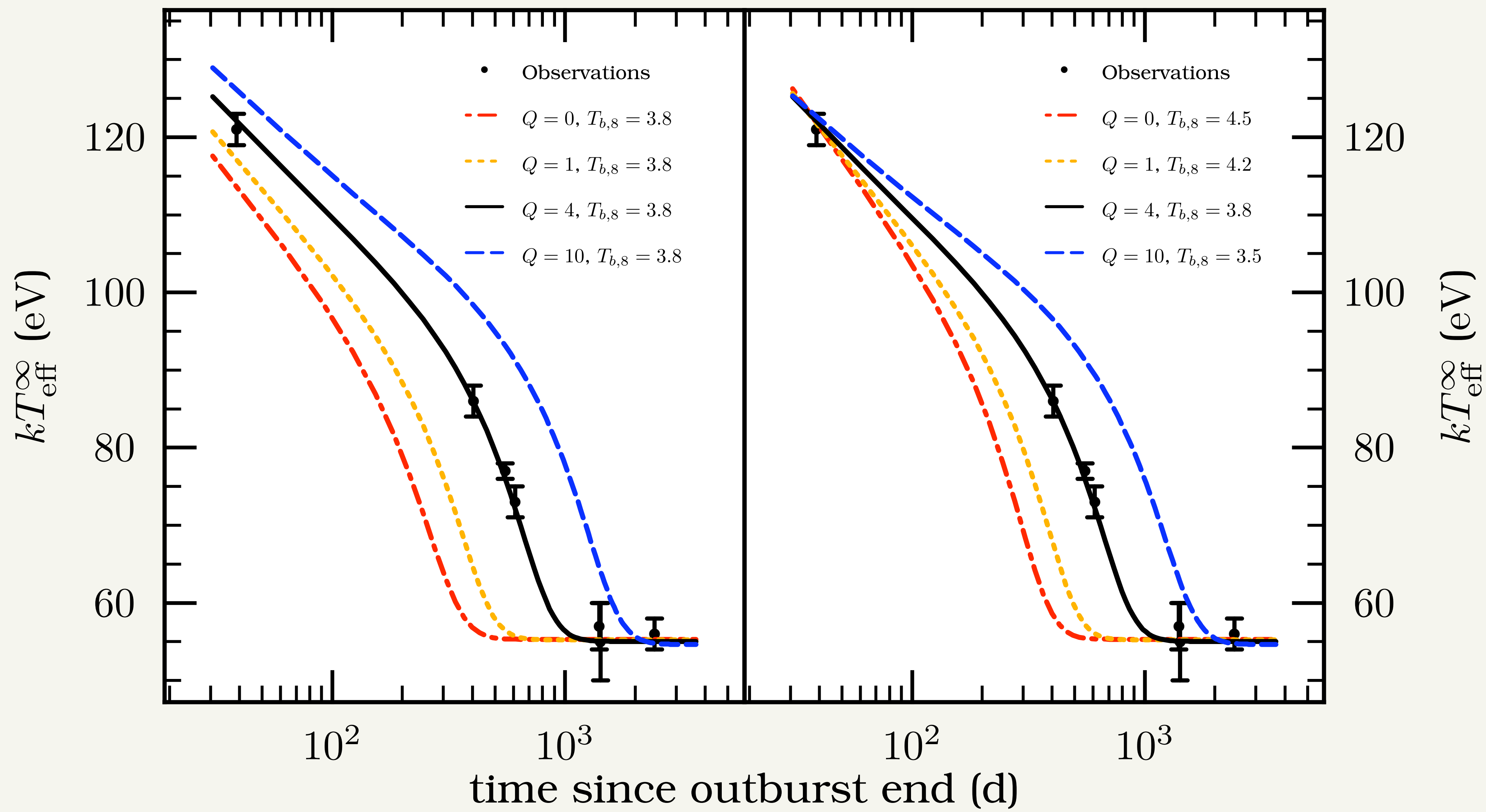
If crust *n* are not superfluid

greater C_P lengthens diffusion timescale



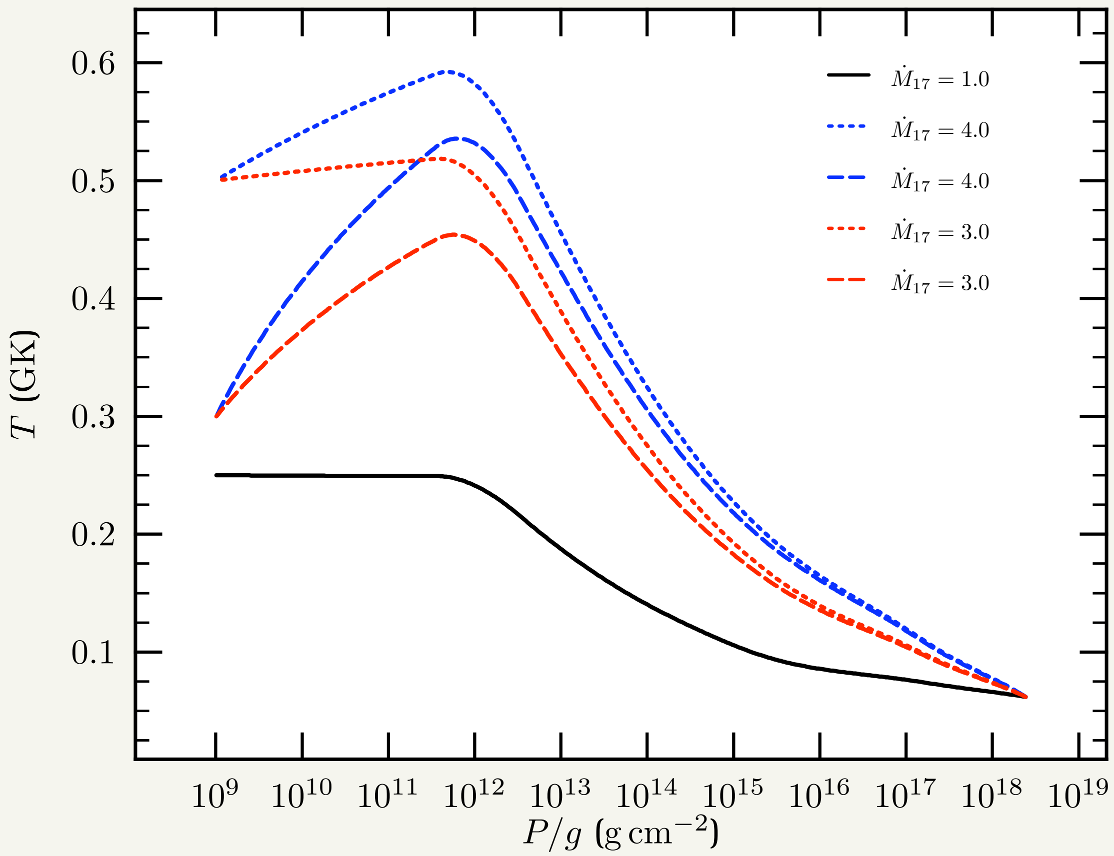


Effect of impurity parameter Q



Shallow Crustal Heating?

- Introduce shallow heat source E_{nuc} = 0.5 MeV/u • (dM/dt)
- Could this explain superburst ignition when accretion rate was higher?
- Observations within 10 days post-outburst could confirm existence of this heating!



summary

- deep crustal heating
  - sets ignition conditions of superbursts, X-ray bursts where stable H burning is unimportant
  - observations of quasi-persistent transients in quiescence
    - crust has high thermal conductivity (agree with Shternin et al. 07)
    - need shallow heat source to fit early part of lightcurve—what is this heating? (pycnonuclear reactions [Horowitz et al. 08]?; other light element reactions?)